Emergent space, emergent time:
a template, an example, some conceptual implications

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Preliminaries on perspective:

- naturalism: metaphysics inferred from physics
- adopt methodological realism (also, simpler language), but not necessarily as metaphysical position

- in fact, sympathetic to participatory and epistemic realism

  existence = playing a crucial (epistemically) role in our (best) models of the world

  not platonism/pitagoreanism - blurred distinction between fictional and concrete, abstract and real, mental and material - what exist (with attributes/properties) is (at) the interface

  objects are not represented by models, they are defined (and brought to existence) by models

  also, reality acquires properties upon interacting (epistemically and empirically) with it

- existence =/= fundamentality

  something may exist simply because it features crucially in some (approximate) corner of our best models, even if it does not feature among the basic, starting/assumed ("fundamental") elements

- key elements in our (best?) theories of quantum gravity are not spatiotemporal (in the sense of our best models of space and time)

  space and time are not fundamental but emergent (they exist but they are not fundamental)

- emergence defined as oriented, binary theoretical relation, by robustness and novelty (and necessarily involves approximations)

J. Butterfield

What is spacetime? what is to emerge?

aspects of space and time

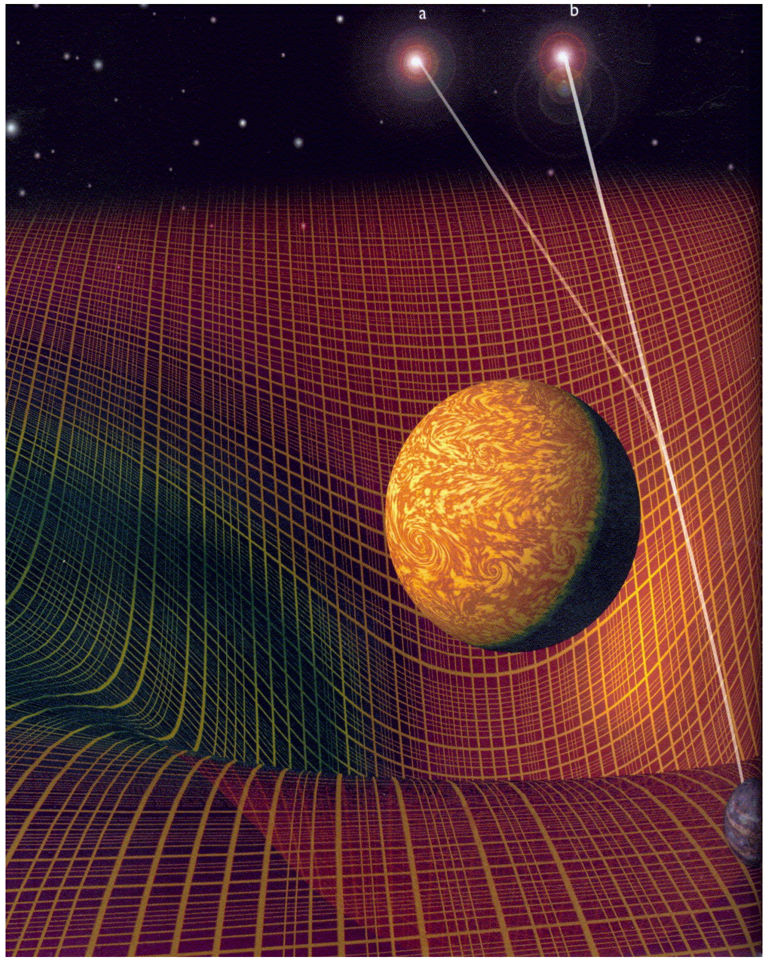
time, space

localization (in time and space) — (possible) events

contiguity (connectedness) — topology

dimension

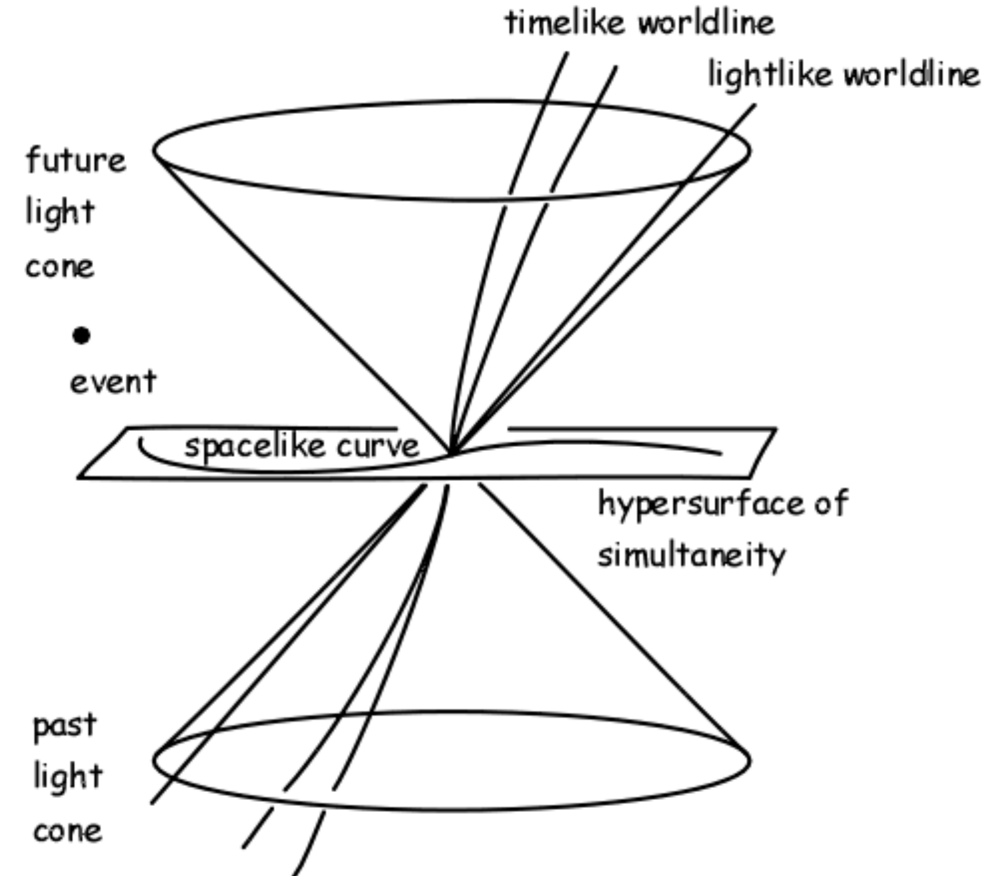
extension (in time and space) — duration, length - geometry



causality

signature

ordering (of events)



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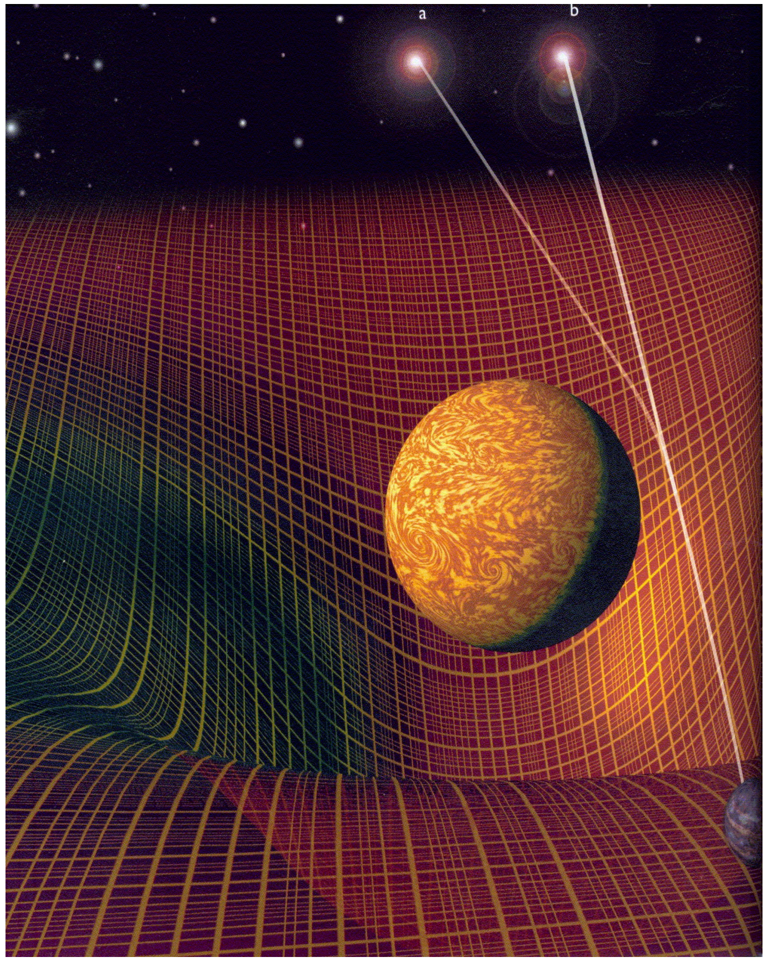

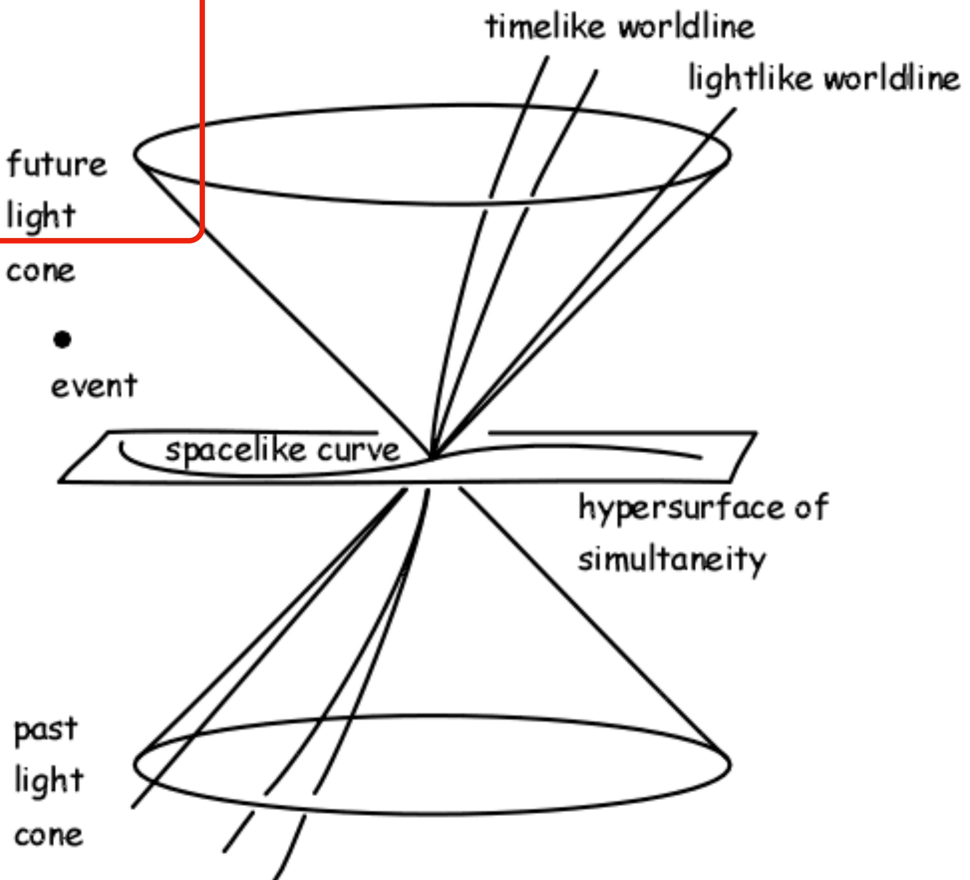

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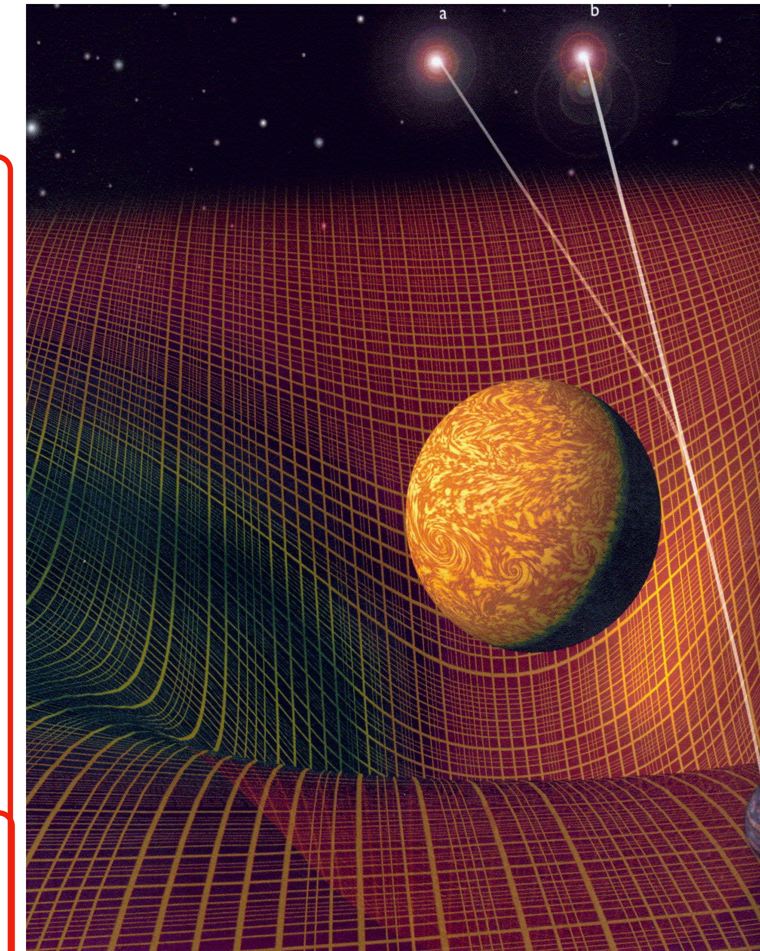

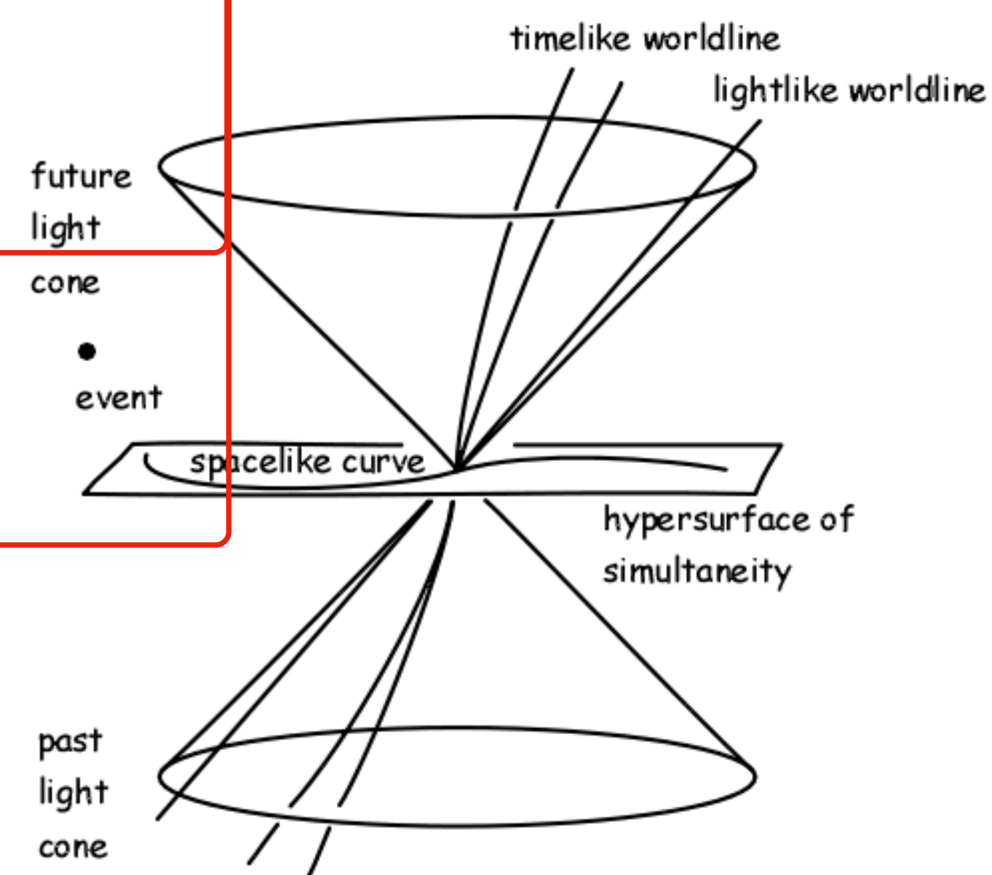

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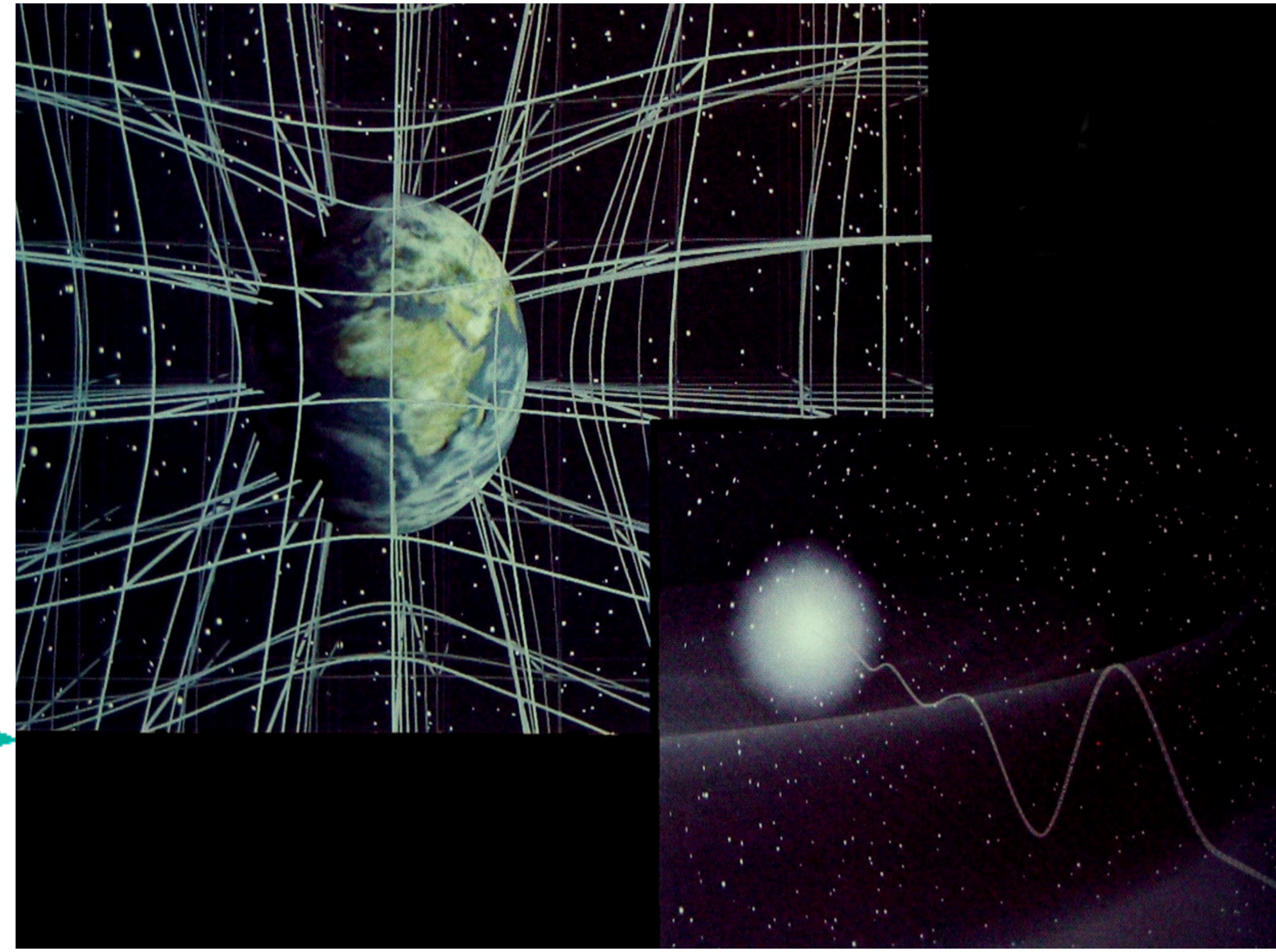
Main lessons from General Relativity (and modern gravitational physics):

spacetime is a physical system

- ingredients of the world: 4d smooth manifold and Lorentzian metric (= "spacetime"), plus several other (scalar, vector, ..) matter fields

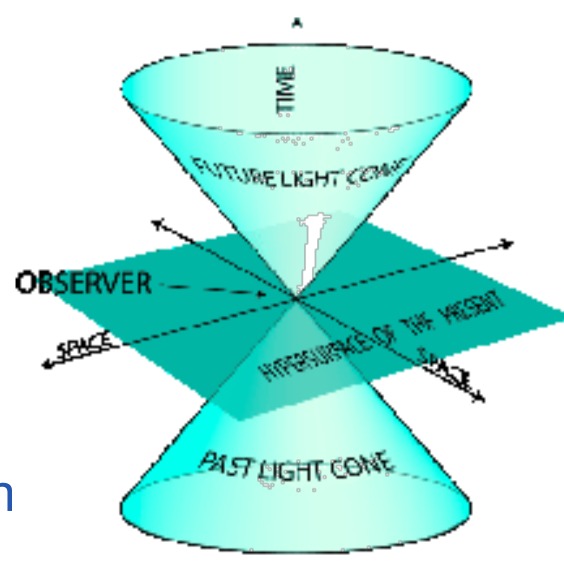
$$(g\,,\,\phi\,,\,\ldots,\,\mathcal{M})$$



- gravity = spacetime geometry

$$g_{\mu\nu}(x) \qquad ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu$$

(spatial distances, temporal duration, causal structure, curvature, ...)



thus,

spacetime itself is a dynamical, physical system

interacting with other physical systems, via Einstein's eqns:

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

- take this description of spacetime (and mathematically/physically equivalent ones) as granted, for now

Emergent gravity vs emergent spacetime

important to distinguish two perspectives and physical possibilities:

- emergent gravity:
    - gravity ~ spacetime curvature and/or dynamical aspects are emergent
    - perturbative or non-perturbative aspects can be considered
    - spacetime (usually, flat Minkowski spacetime) is fundamental
    - examples in condensed matter (eg analogue gravity) and perturbative quantum gravity

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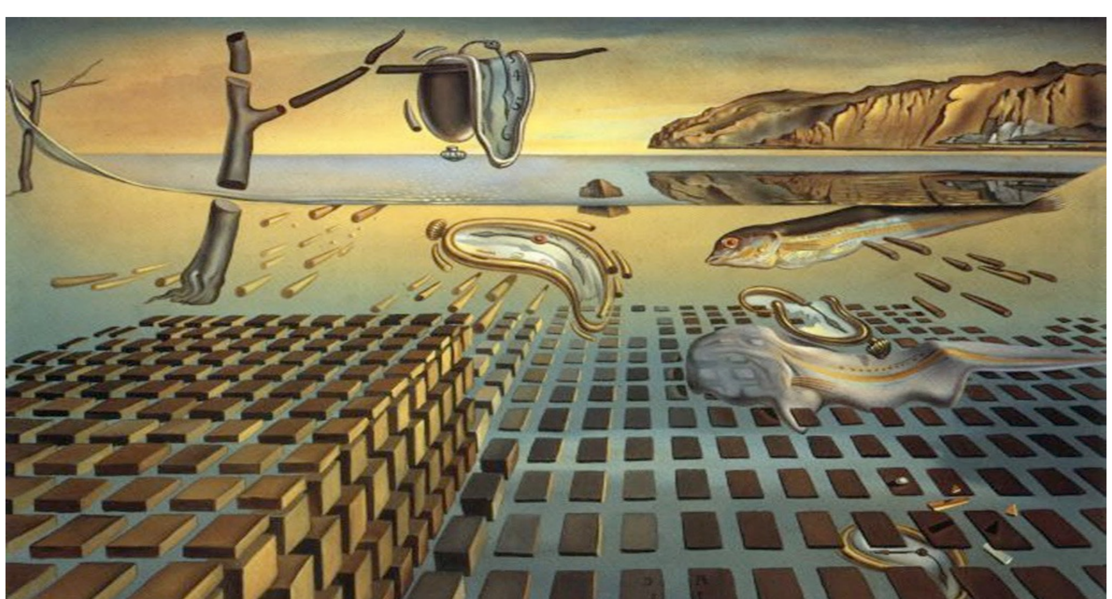

new (quantum) dofs?

discrete structures?

pure algebraic data?

which "dynamics"?

Background independence vs general covariance vs diffeomorphism invariance

naive view: spacetime = manifold + metric + fields defined on the manifold

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-different- tensor field $GL(4,\mathbb{R})$ irrep for φ

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simply requirement that eqns are geometrically well-defined - any theory can be written as such

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- thus, full diffeomorphism invariance = only invariant background structures or no background structure

  - in this sense: diffeomorphism invariance = background independence

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in GR/QG, only diffeo-invariant quantities are physical (thus encode spacetime properties) $\longrightarrow$

the differentiable manifold, its points, directions, atlases and associated coordinate systems are unphysical

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fields themselves (as functions of manifold points) are unphysical objects $g_{\mu\nu}(x)$ $A_\mu(x)$ $\varphi(x)$

GR, as usually formulated, is written in a (useful) highly redundant language

Spacetime localization is relational

relational strategy

Rovelli, Dittrich, Ashtekar, Bojowald, Gambini, Giddings, Giesel, Kaminiski, Lewandowski, Marolf, Pullin, Thiemann, Chataignier, PH, Husain, Pons, Salisbury, Singh, Sunderymeyer, Tambornino, Tsobanjan, …

Relational observables: "functions on reference fields"

correlations on superspace (space of fields)

what is a reference system?

- As non-invariant/asymmetric under gauge symmetries as possible (invariants worst possible reference systems)
- As many DoFs as there are indep. gauge directions (want to parametrize orbits with dynamical reference DoFs)

$\Rightarrow$ **reference DoFs are gauge DoFs**

How do we describe physics relative to dynamical reference systems?

identify some dynamical fields as clock/rods and use their values to label evolution/localization of other dynamical fields

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summary

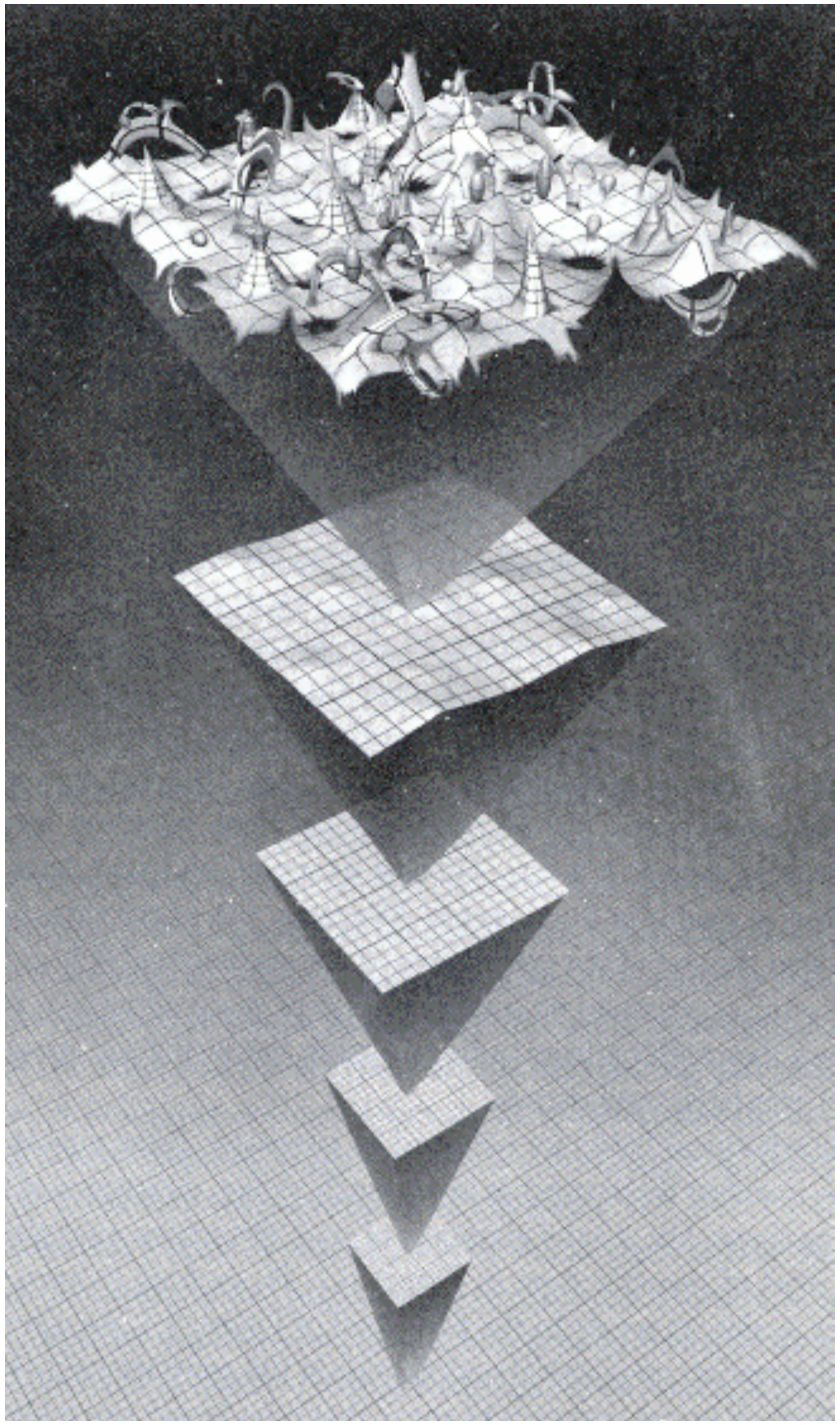
to identify "spacetime = manifold" or "spacetime physics = physics on manifold" is approximation at best

(corresponds to case in which set of four scalar fields behave like test fields covering manifold, and can be used as coordinates for manifold points)

do not expect to find manifold etc neither at fundamental QG level, nor in its effective description

background structures in GR and QG?

- GR has some diffeo-invariant background structures, which could be maintained in QG
  - spacetime dimension
  - topology
  - signature
  - "internal" Lorentz symmetry



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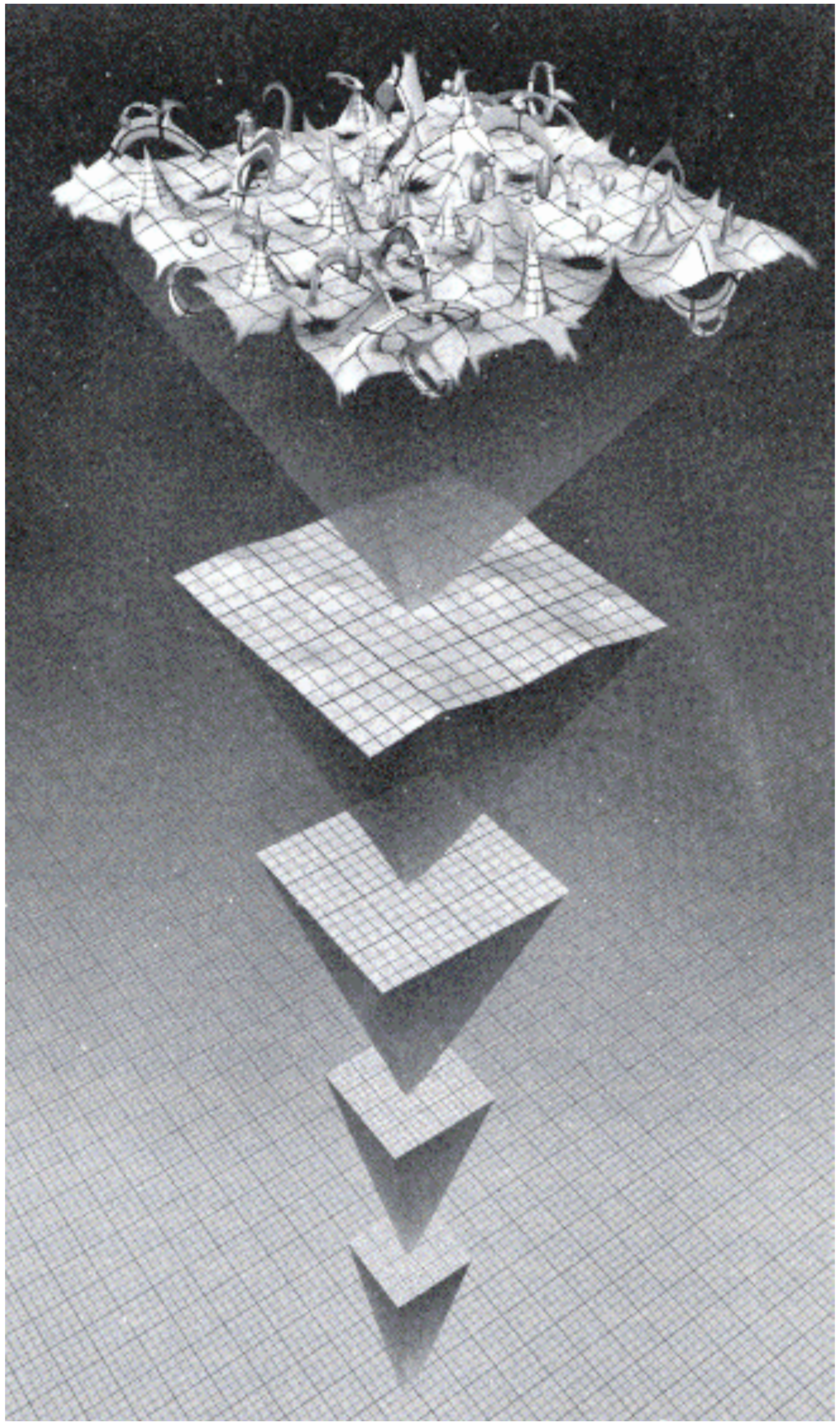

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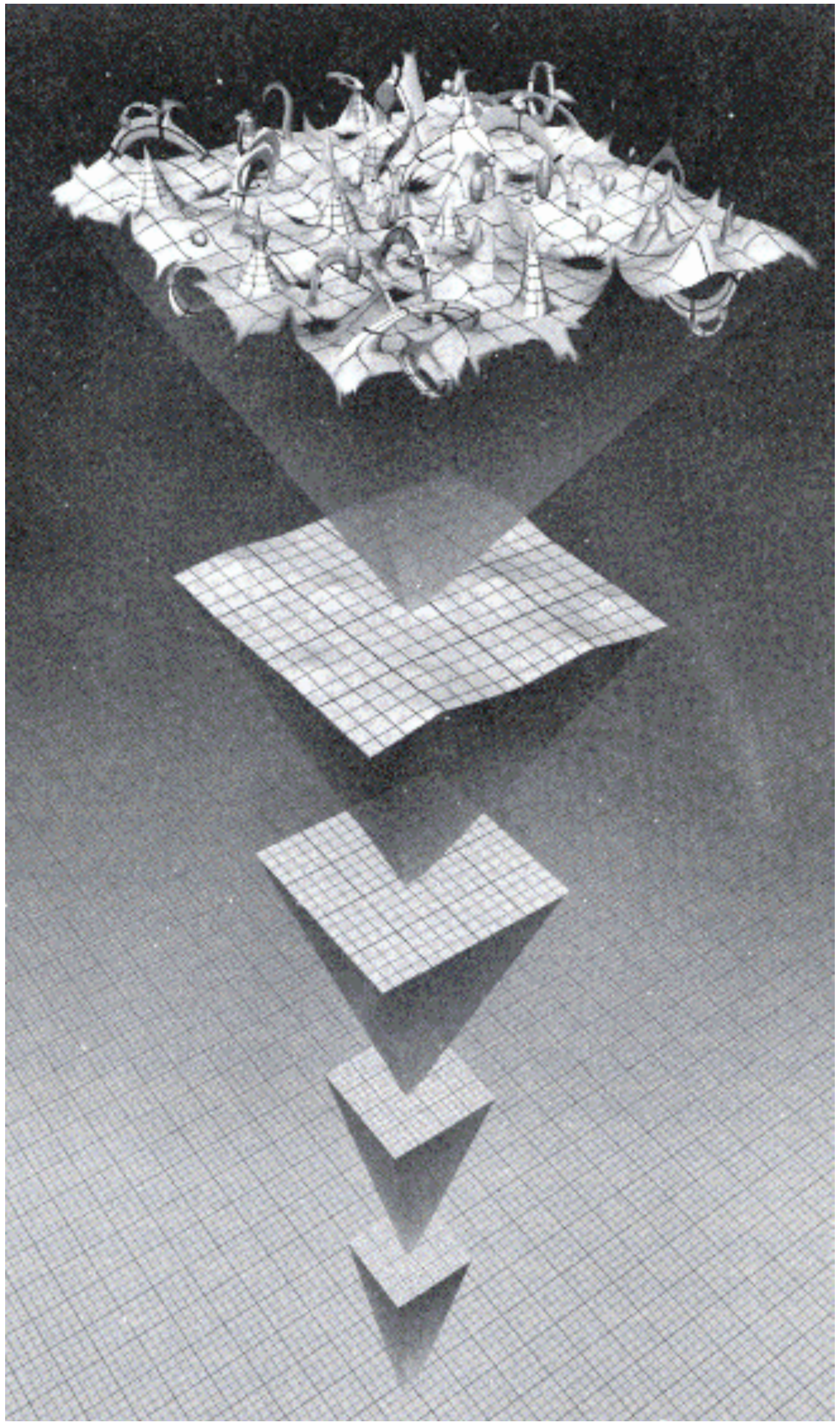

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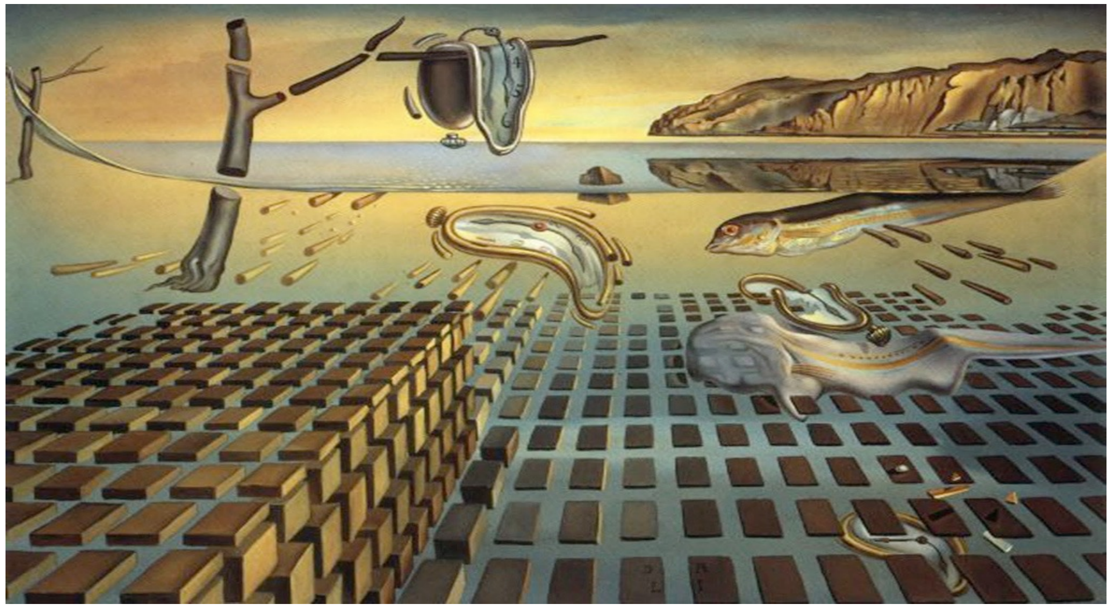
emergent spacetime scenarios will be the more radical
the more of these ingredients are dynamical & emergent

any emergent spacetime scenario that assumes one or more of
these ingredients may be less radical than hoped, but does not
violate the background independence of GR

Steps to emergence

Identify fundamental structures/ontology + dynamics



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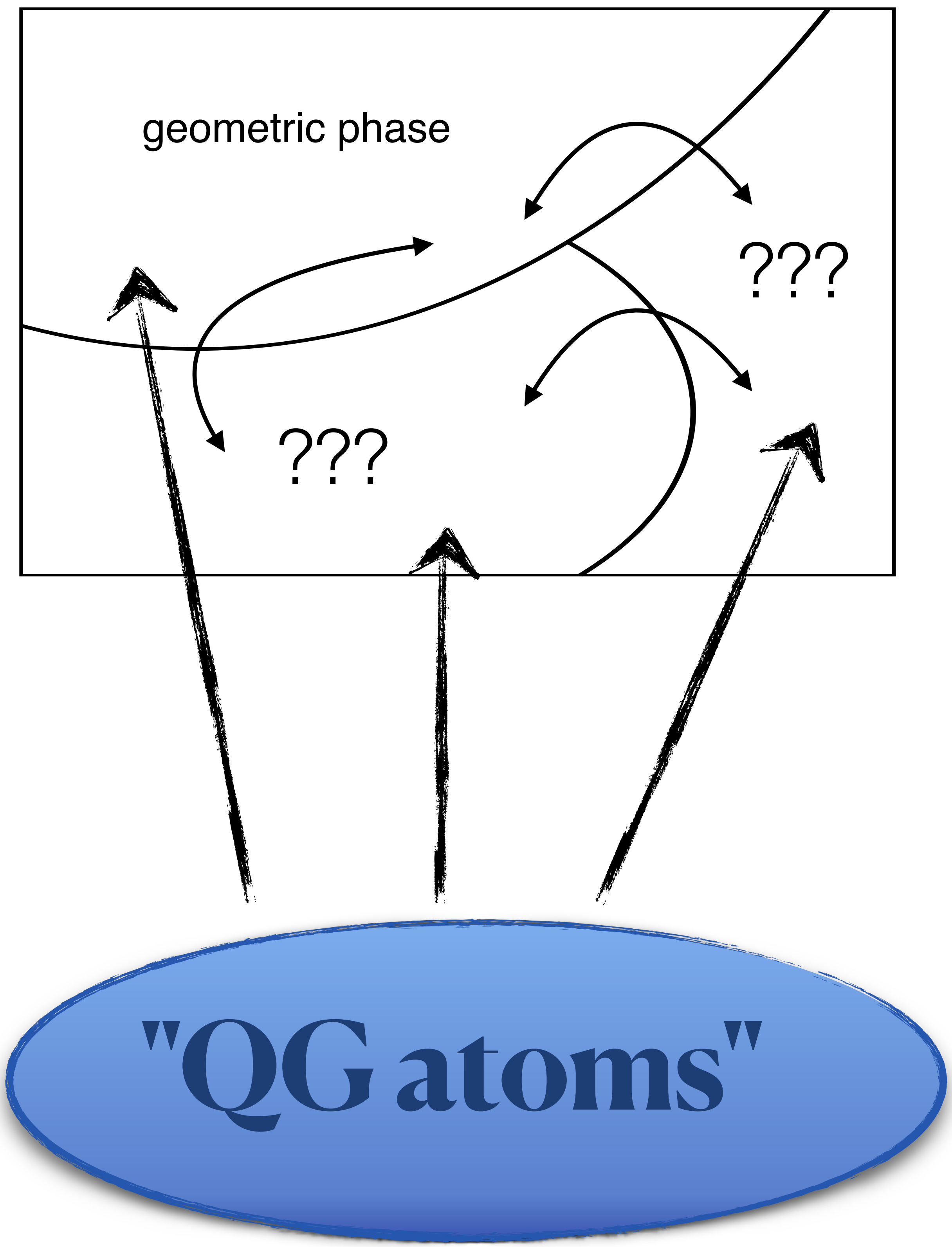
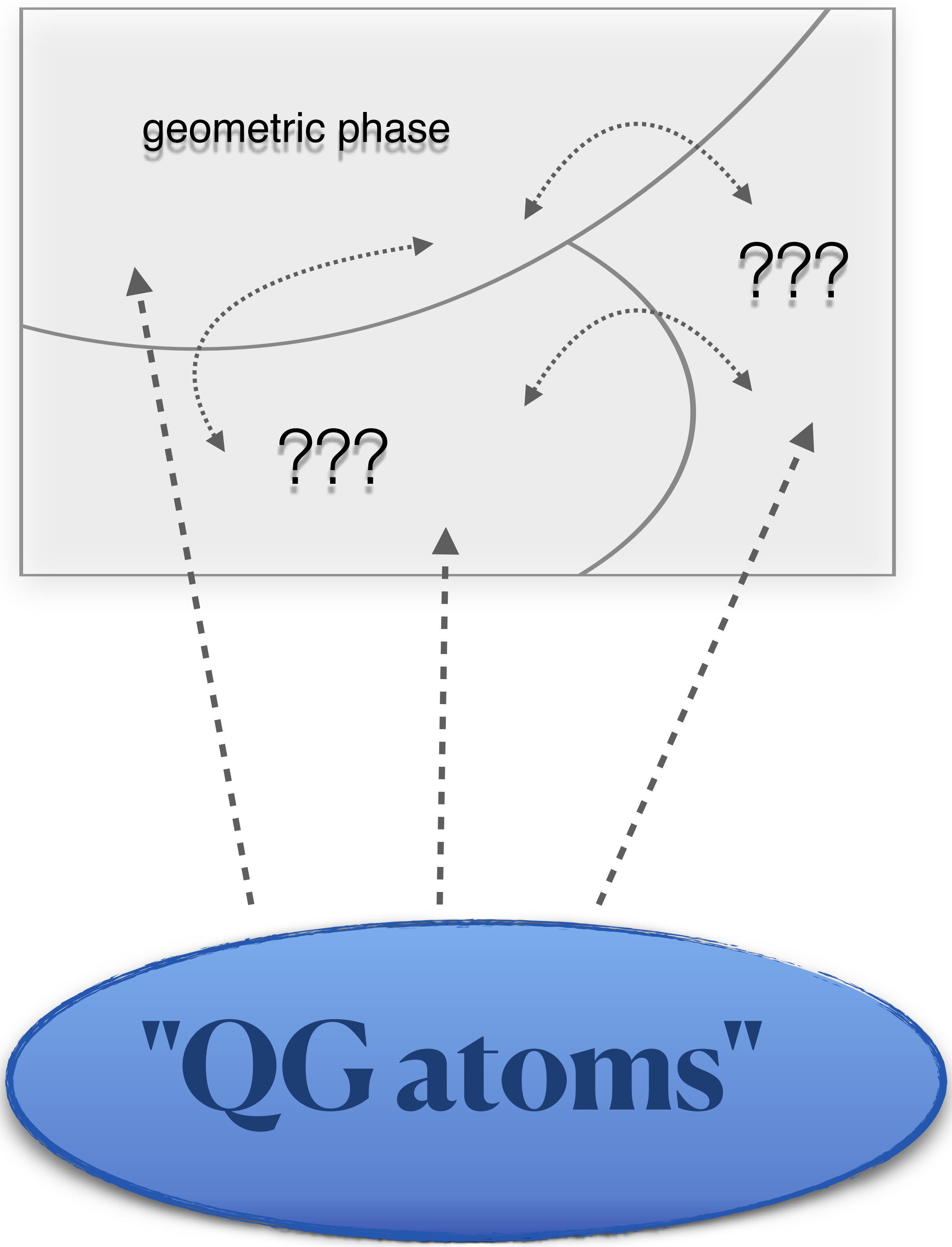
which "dynamics"?

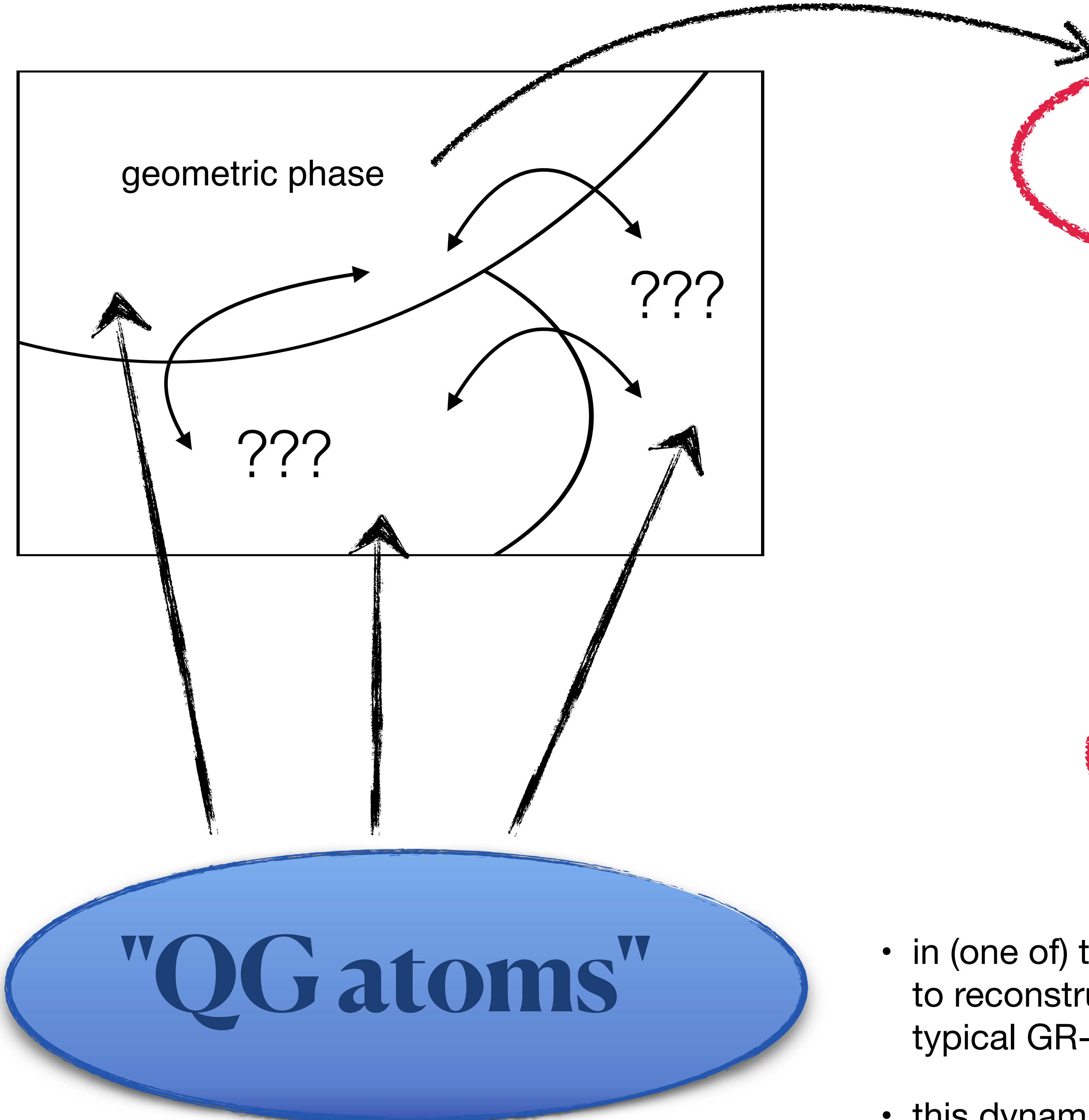
- starting point can be postulated or (partially) derived, from discretizing continuum structures, from "quantizing" classical entities, from analyzing notions of geometry/topology/causality
- it can be more or less radical, i.e. more or less close to GR and QFT and their structures
- same for fundamental dynamics
- quantum mechanics can be assumed, knowing that it requires novel interpretation and use anyway, or one can adopt generalised framework
- most steps required to go from fundamental structures/dynamics to emergent spacetime are same

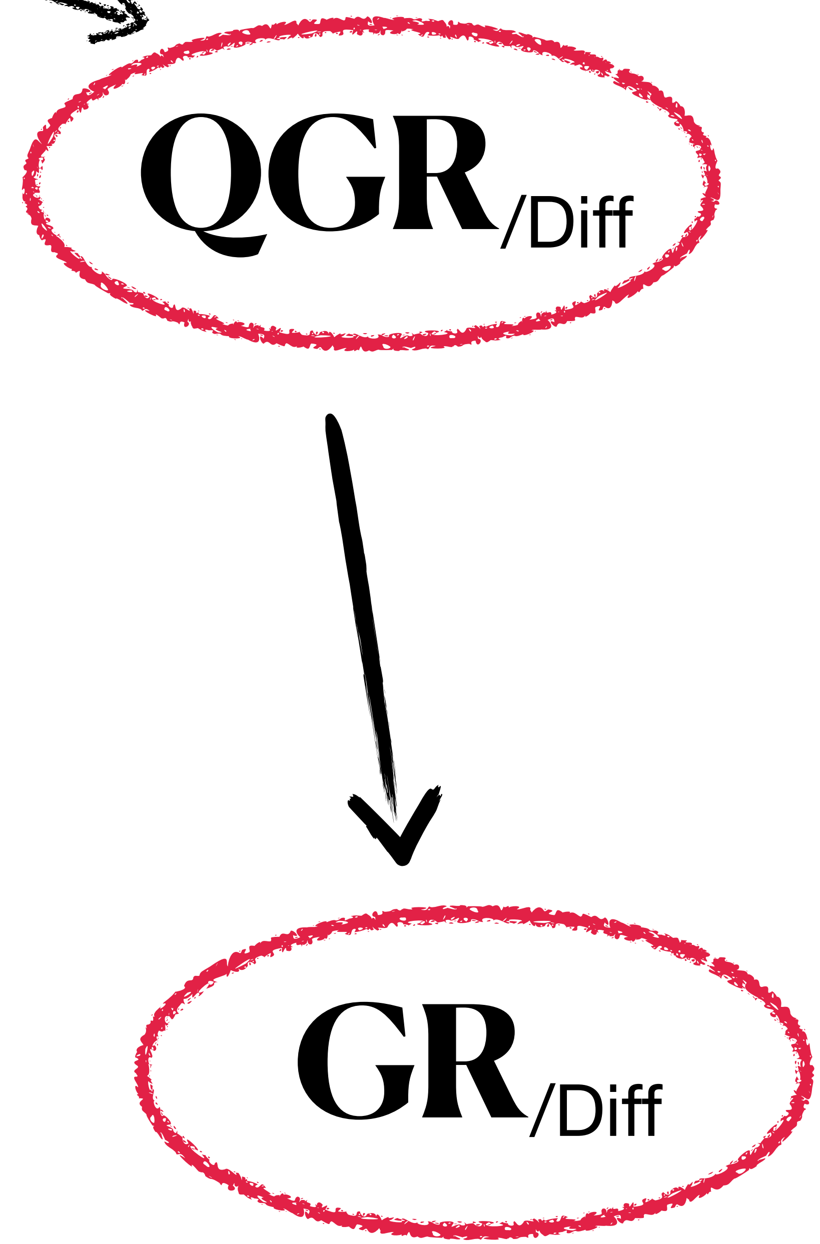


- some form of "continuum limit", i.e. control over collective dynamics of (more and more of) all the dynamical dofs of the fundamental theory
- it cannot be expected to be unique - different continuum phases (with associated transitions)
- at least one phase should be "geometric", i.e. admit the reconstruction of a spatiotemporal description



- some form of "continuum limit", i.e. control over collective dynamics of (more and more of) all the dynamical dofs of the fundamental theory
- it cannot be expected to be unique - different continuum phases (with associated transitions)
- at least one phase should be "geometric", i.e. admit the reconstruction of a spatiotemporal description
- the limit and the control will be approximate only
- the need for approximation is not a nuisance, it is a constitutive feature of emergence

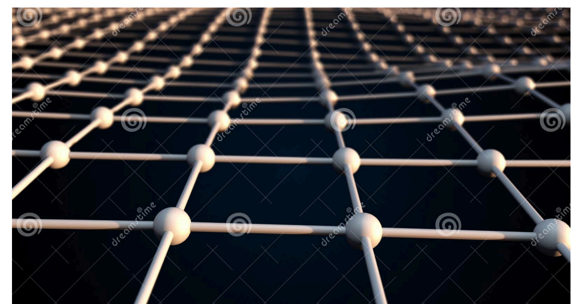




- in (one of) the geometric phase(s), it will be possible to reconstruct a gravitational dynamics with the typical GR-like ingredients (fields and symmetries)
- this dynamics may still be in part or fully of quantum nature/origin
- if so, a further approximation will be needed to recover a classical GR-like description

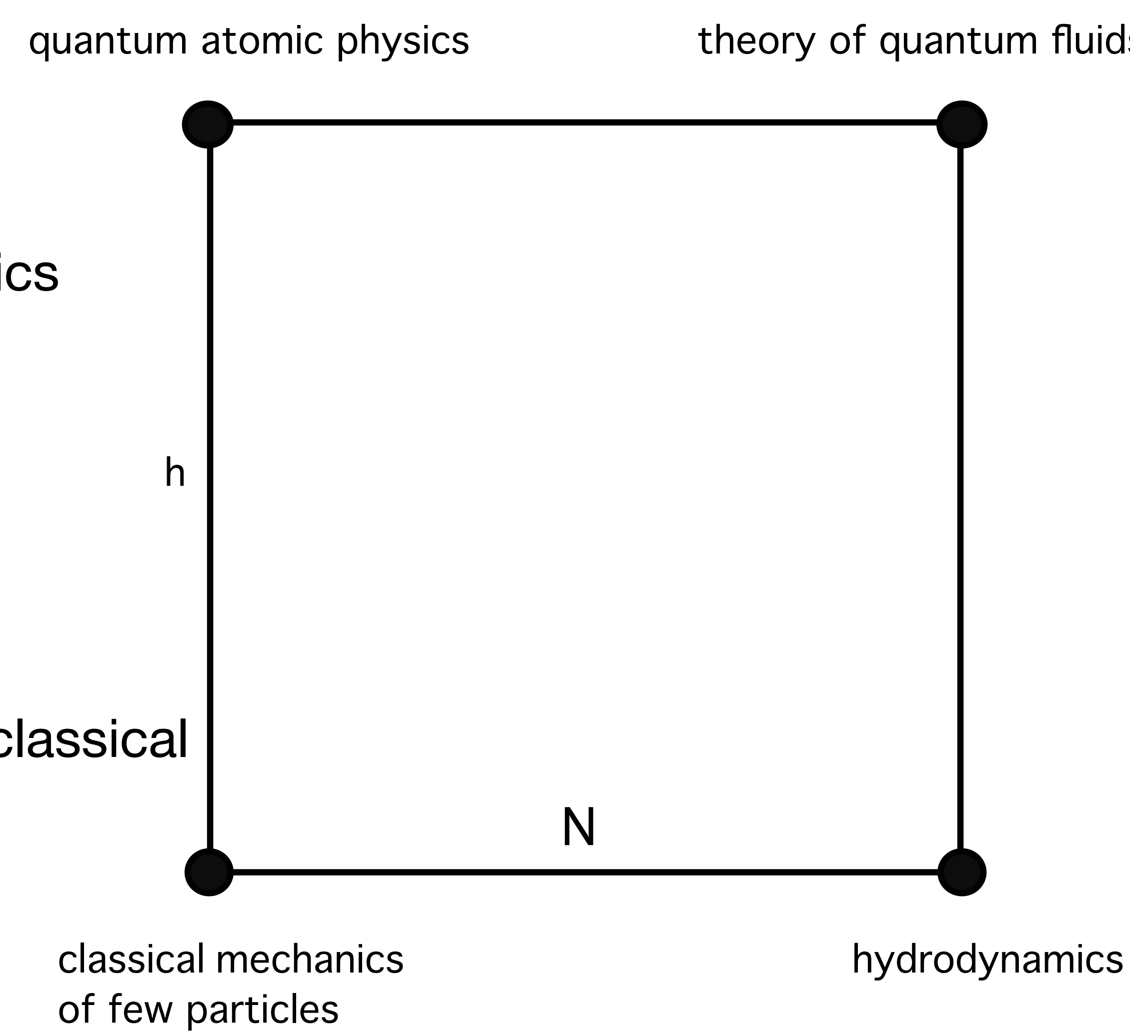
continuum approximation (limit) vs classical approximation (limit)

- classical approximation
  - definition: quantum effects become negligible
  - with respect to which observable? states can be semi-classical wrt different observables
  - example: $$\widehat{A}_S = \sum_s \widehat{a}_s$$



quantum states semiclassical wrt a_s are not semiclassical wrt A_S (and vice versa)

- continuum approximation
  - definition: limit of large # dofs - collective physics
  - examples: from molecular physics to hydrodynamics



conceptual difference

non-commutativity (in general)

possibly related: collective physics may be inherently classical wrt some (eg macroscopic) observables

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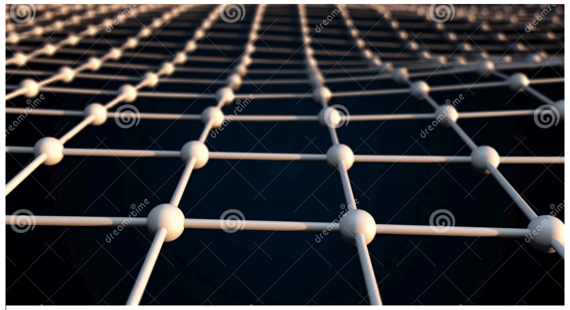

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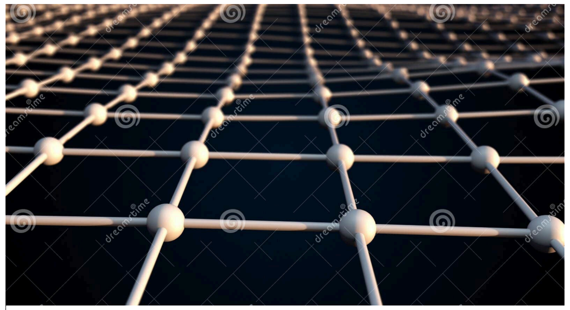

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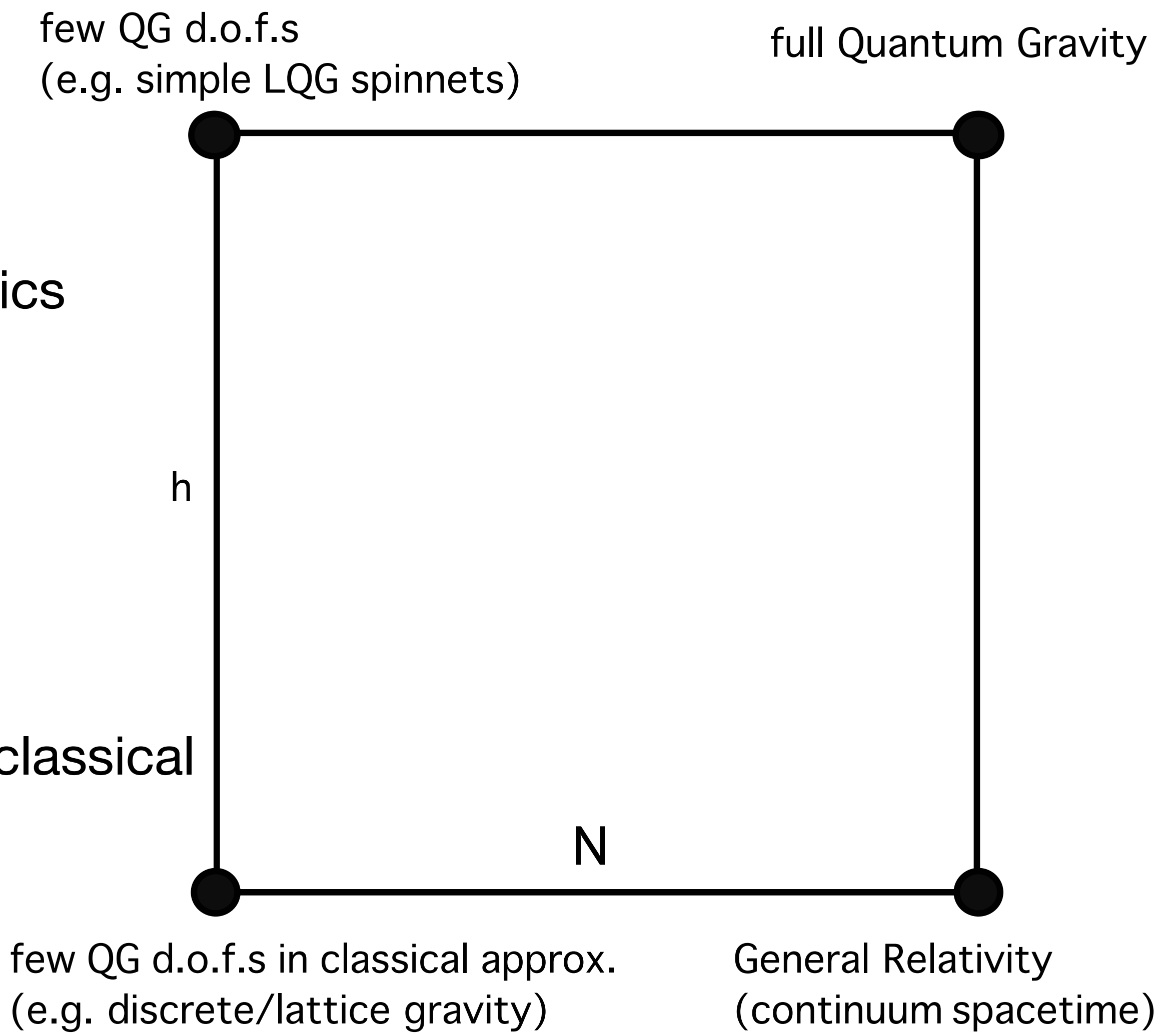
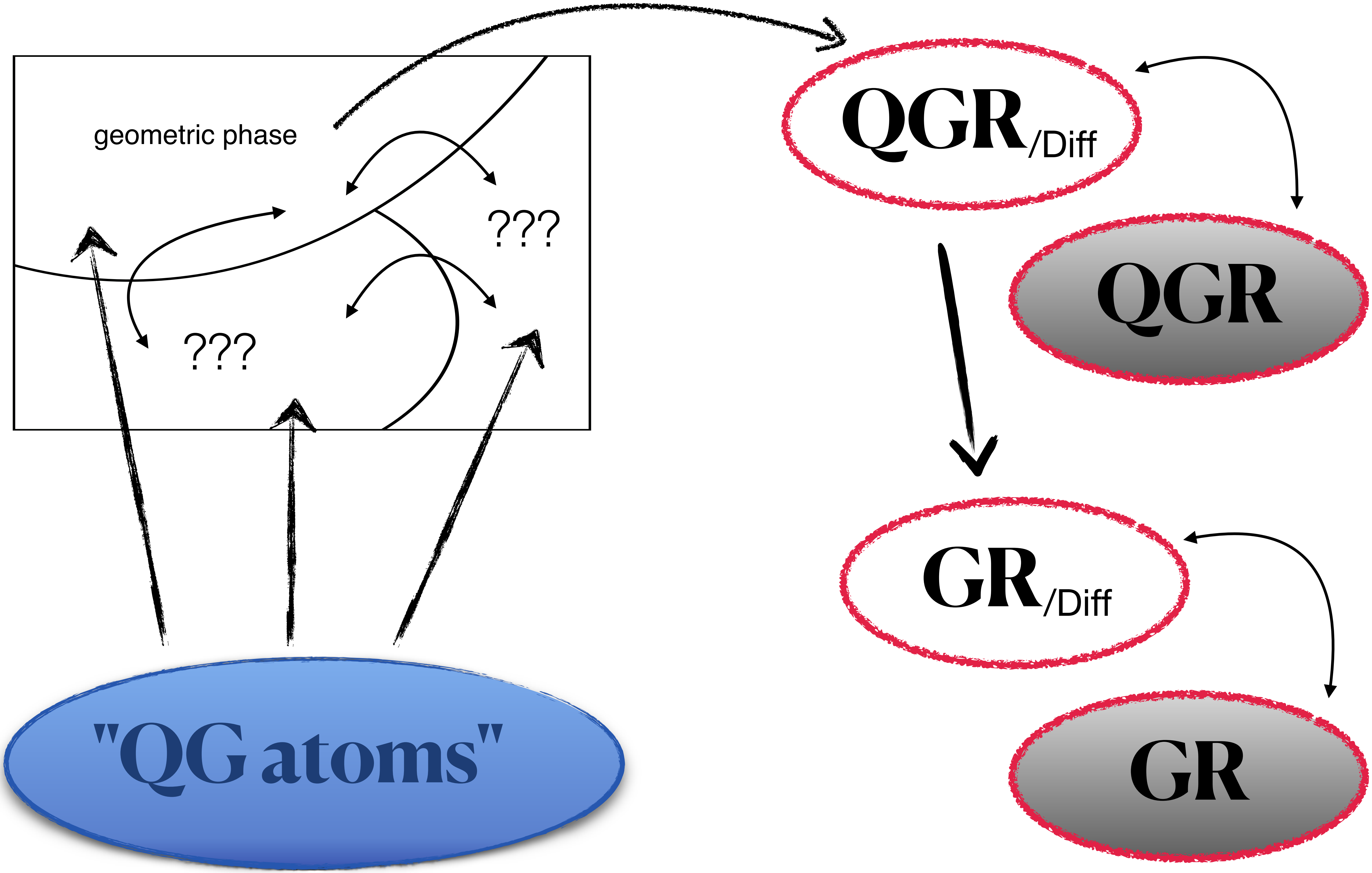
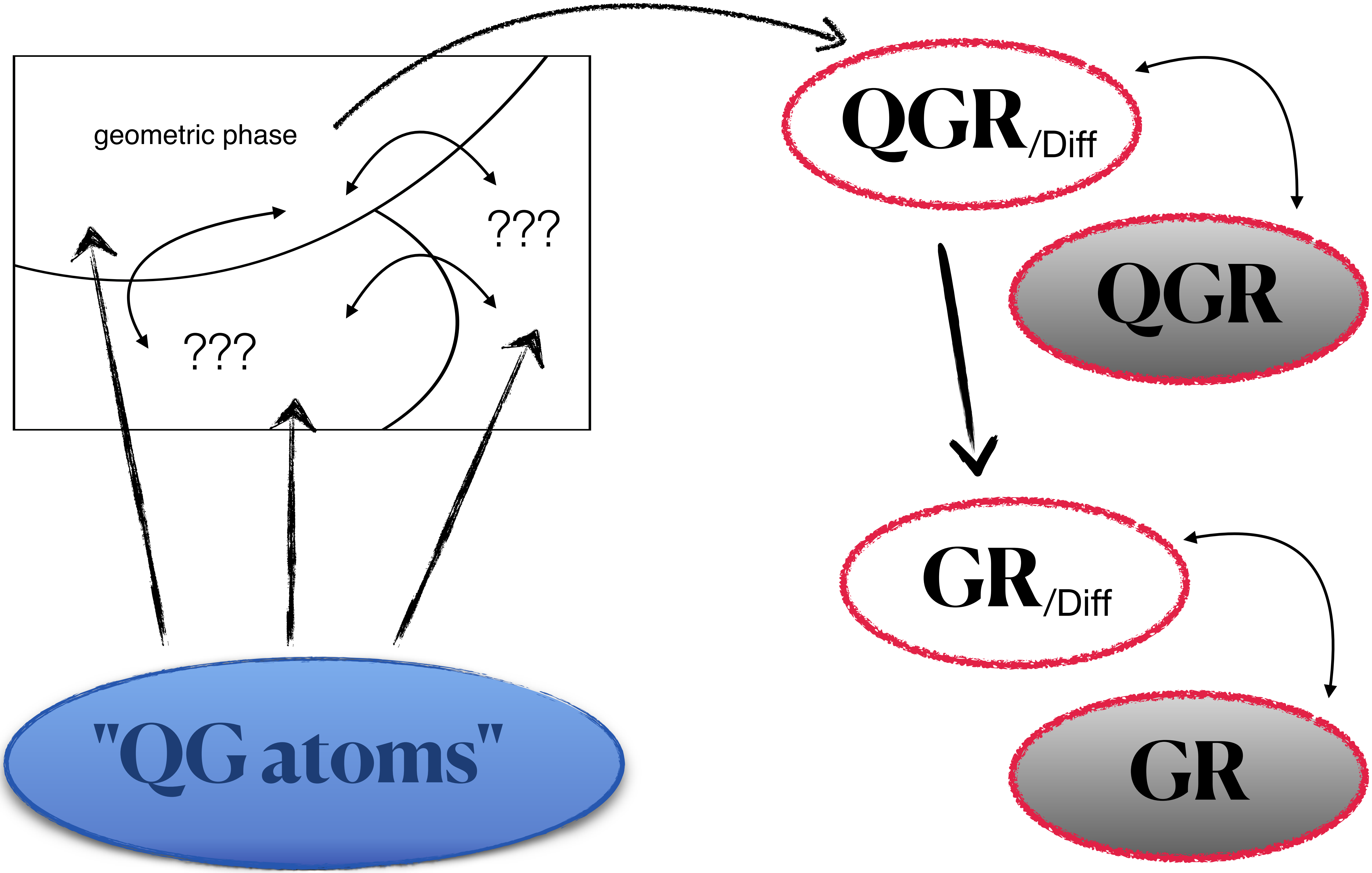




- at any point, the truly physical, (approximately) local spatiotemporal content of the theory has to be expressed in relational observables
- diffeomorphism redundancy will either not be present at all, or have to be removed to elucidate the actual physical content



Important:

these steps are not sequential nor all individually necessary

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Observational signatures of fundamental structures

- this scheme and most technical challenges and procedures apply equally both if the starting "non-spatiotemporal" structures are understood as physics (new ontology) and if they are understood as mere technical/mathematical tools/artefacts
- they can sensibly be understood as physical only if they lead to direct or indirect observational signatures (unless one can show/argue logical necessity)

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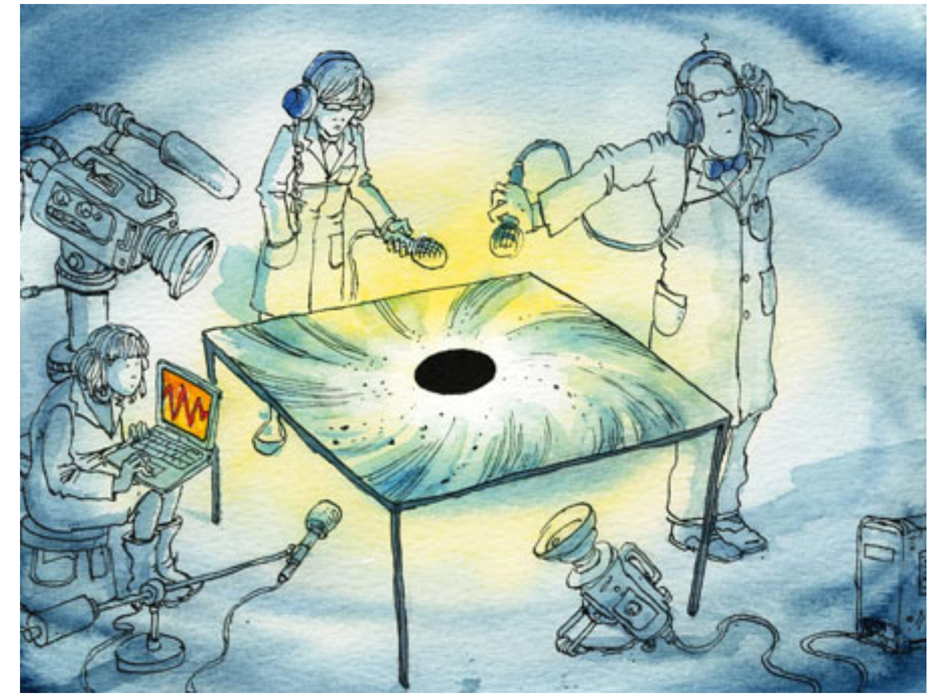

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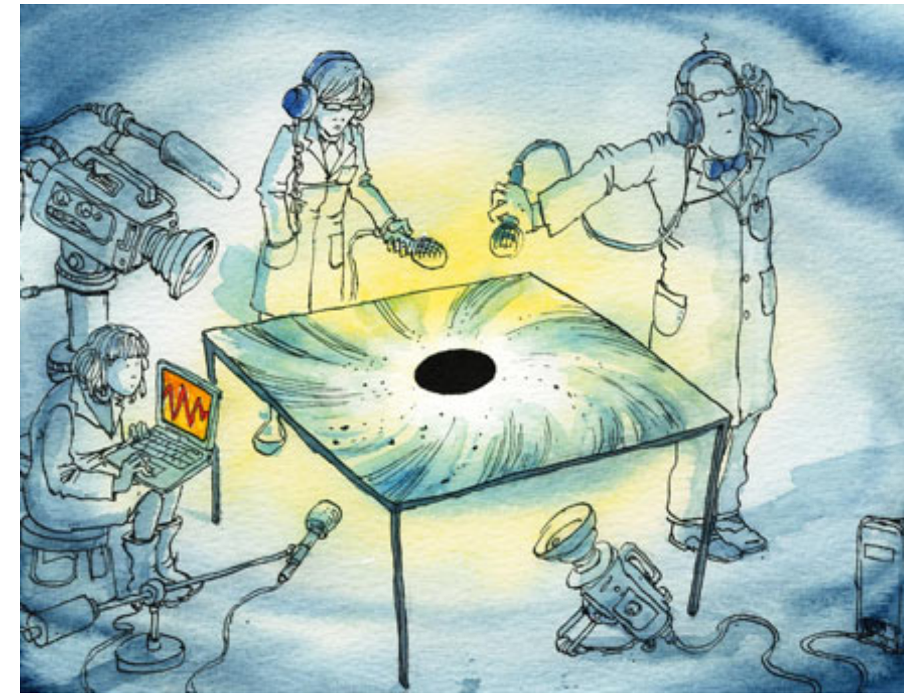

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what sort of observational signatures?

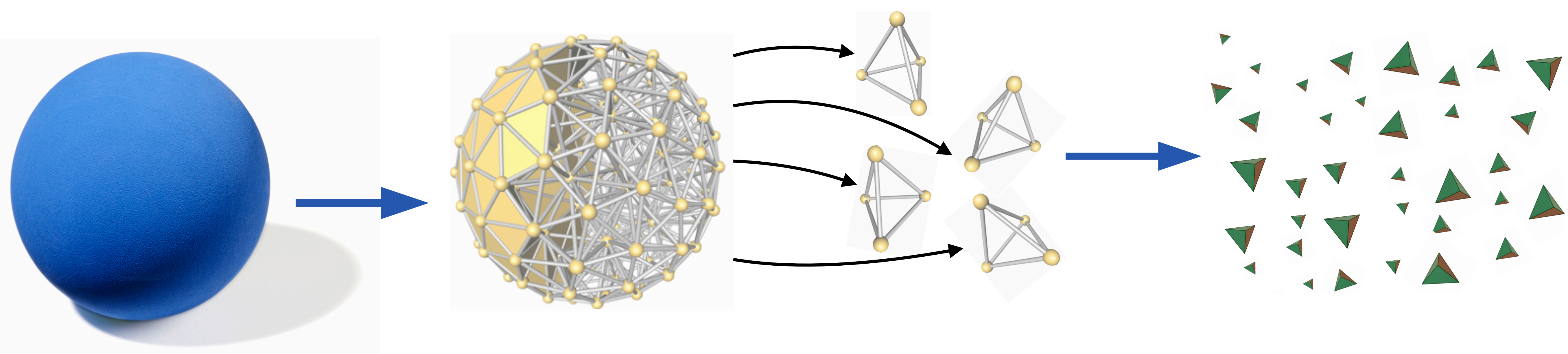
- it depends on the nature of the fundamental structures, which which of the usual spacetime elements are emergent, what sort of approximations are needed for emergence, ...
- in principle, if spacetime is emergent we could expect deviations to the usual notions of:
    - locality
    - causality
    - unitarity
    - spacetime symmetries
    - equivalence principle

- moreover, in an emergent spacetime scenario, we cannot assume/expect any separation of scales - quantum gravity effects can appear at low and high energies, small and large distances

Spacetime emergence from quantum gravity:
an example

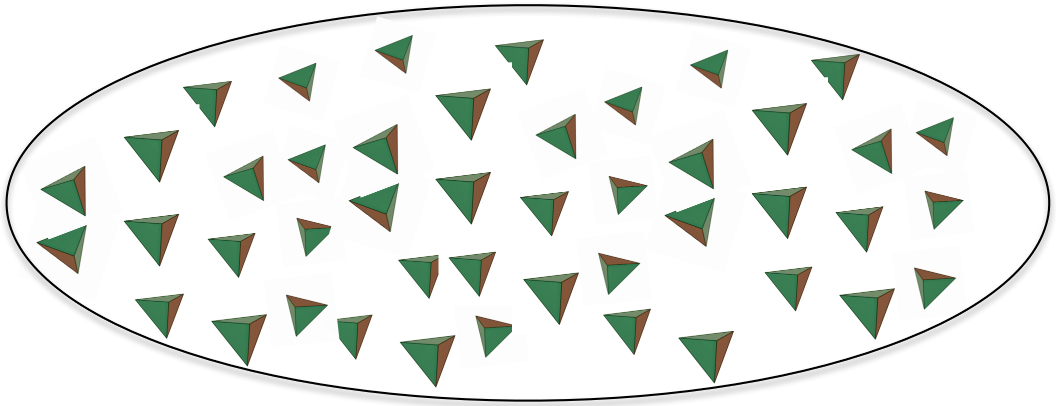
Tensorial Group Field Theories:

quantum field theories OF spacetime ("atoms")



Boulatov, Ooguri, Barrett, Crane, De Pietri, Freidel, Krasnov, Rovelli, Reisenberger, Perez, DO, Livine, Baratin, Chirco, Colafranceschi, Girelli, Ryan, Gurau, Kotecha, Vitale, Rivasseau, ...

TGFT

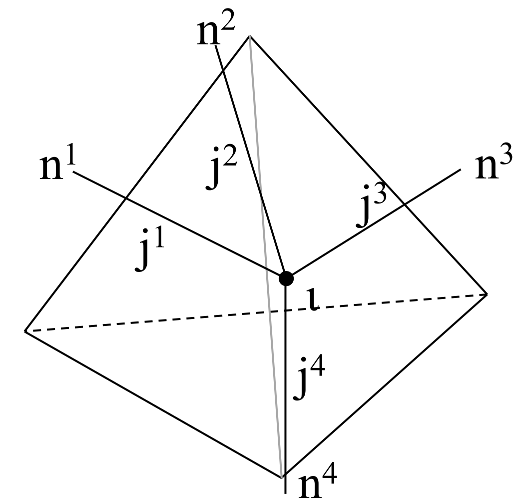


Hilbert space of quantum tetrahedron

(in terms of SU(2) irreps)

spin network vertex ~ quantum tetrahedron

$$\mathcal{H}_v = \bigoplus_{\vec{j}_v} \left(\bigotimes_{i=1}^{d} \underbrace{V^{j_v^i}}_{\text{repr. space}} \otimes \underbrace{\mathcal{I}^{\vec{j}_v}}_{\text{intertwiner space}} \right)$$

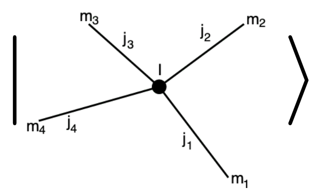


quantum geometric operators (triangle areas, volume,...) act on this Hilbert space

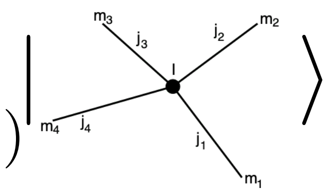
+ additional "geometricity" constraints that can be imposed at dynamical level

e.g. area operator $\widehat{A}_{\triangle_i}$

e.g. volume operator $\widehat{V}$



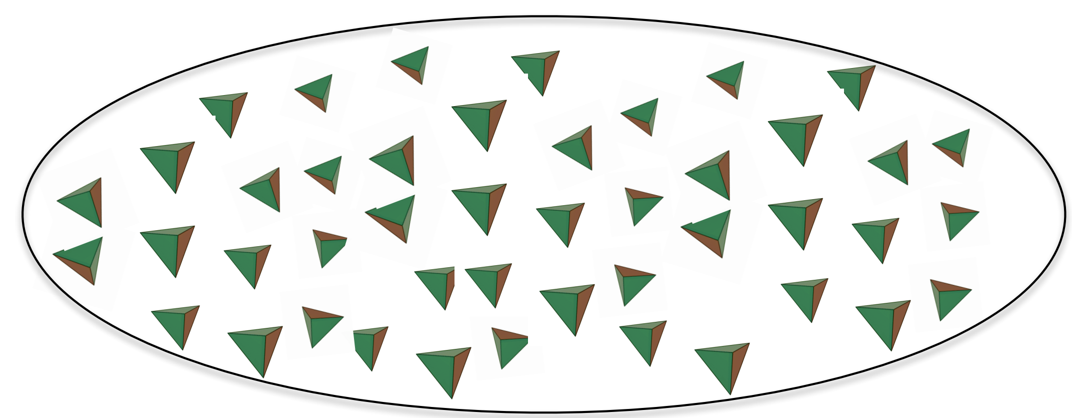
$= A_{\triangle_i}(j_i)$, $V(I(\{j_i\}))$



→ GFT Fock space $\mathcal{F}(\mathcal{H}_v) = \bigoplus_{V=0}^{\infty} sym \left\{ \left(\mathcal{H}_v^{(1)} \otimes \mathcal{H}_v^{(2)} \otimes \cdots \otimes \mathcal{H}_v^{(V)} \right) \right\}$ + 2nd quantized operators

"2nd quantized Loop Quantum Gravity"

TGFT



Quantum states of many quantum tetrahedra

- full Hilbert space (arbitrary number of (connected or disconnected) tetrahedra):

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- GFT field operators (creating/annihilating spinnet vertices/tetrahedra):

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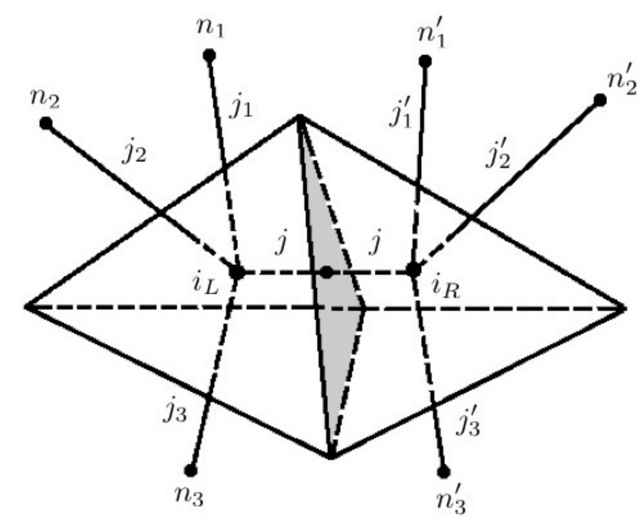
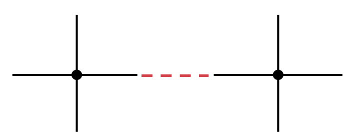
- gluing quantum tetrahedra with entanglement — E. Colafranceschi, DO, '21



link state

quantum states for extended simplicial 3-complexes (spin network graphs) = entangled many-body states of many quantum tetrahedra (spin network vertices)

$$|\psi\rangle \xrightarrow[\text{}]{\text{gluing (entangling edge dof)}} |\psi_\gamma\rangle = \left(\bigotimes_{e\in L}\langle e|\right)|\psi\rangle$$



many- body wave-function for V open vertices

maximal entanglement

internal links of combinatorial pattern γ

$$|e\rangle = \bigoplus_j \frac{1}{\sqrt{d_j}} \sum_n |jn\rangle \otimes |jn\rangle$$

maximally entangled state of edge degrees of freedom

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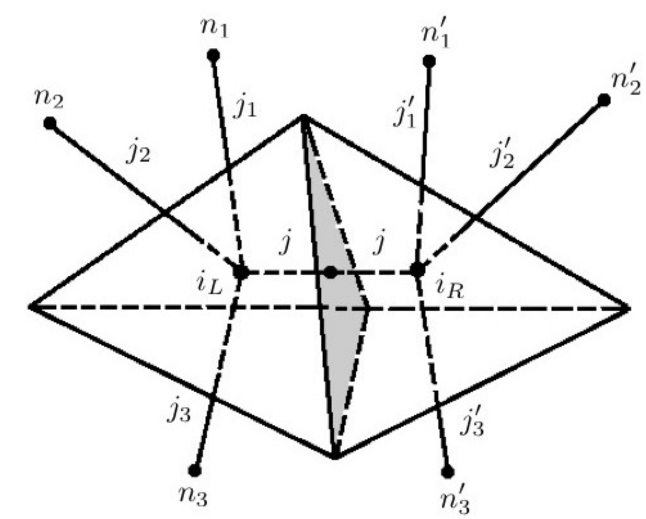

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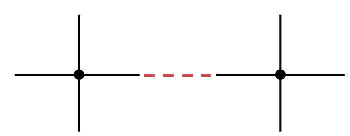

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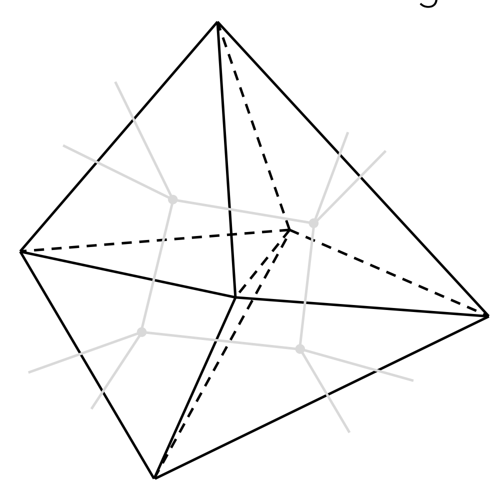
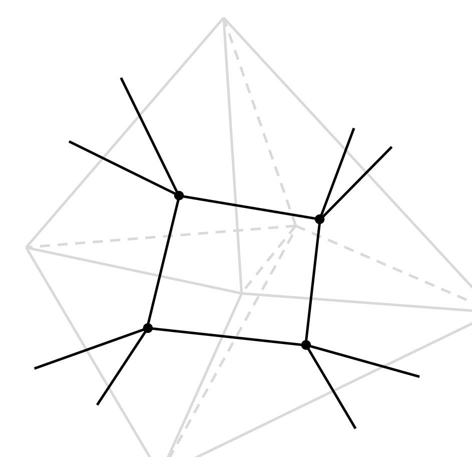
- spin network states for arbitrary graphs
  ~ arbitrary quantum simplicial lattices





- can show "discrete entanglement/geometry correspondence"
- same kind of quantum states as in LQG and lattice quantum gravity, but even less "spatiotemporal interpretation"

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spin network vertex ~ quantum tetrahedron

(in terms of SU(2) irreps)

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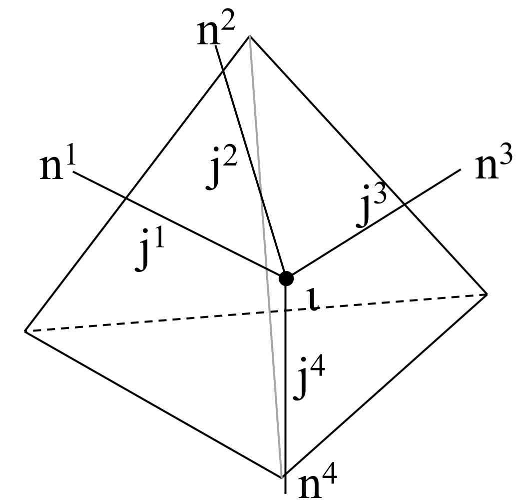

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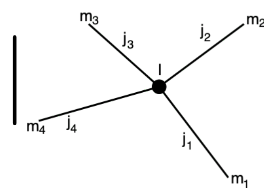
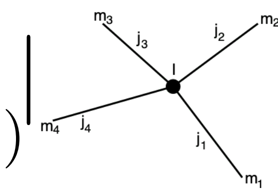
$$\Big| \; $$  $$\Big\rangle = A_{\triangle_i}(j_i) \;\; V(I(\{j_i\})) \Big| \; $$  $$\Big\rangle$$

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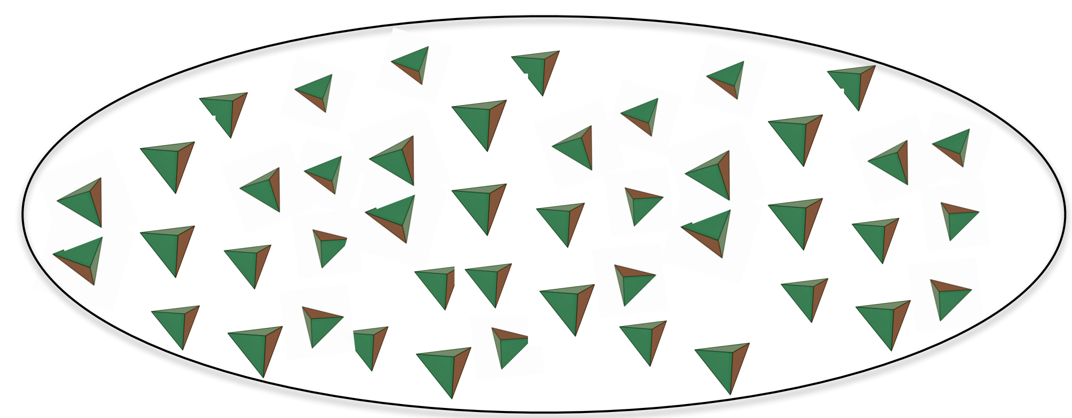

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- main guideline for model building

define models that produce, in perturbative expansion (i.e. where lattice structures are relevant),

- interaction processes (Feynman diagrams) of quantum simplices corresponding to 4d lattices of any topology
- quantum (Feynman) amplitudes given by lattice gravity path integrals (coupled to scalar fields)

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(combines ideas of quantum Regge calculus and dynamical triangulations)

Feynman amplitudes (model-dependent) = sum over group-theoretic data (group elements, Lie algebra elements, group irreps) weighted by amplitude related to discrete gravity ~ spin foam models

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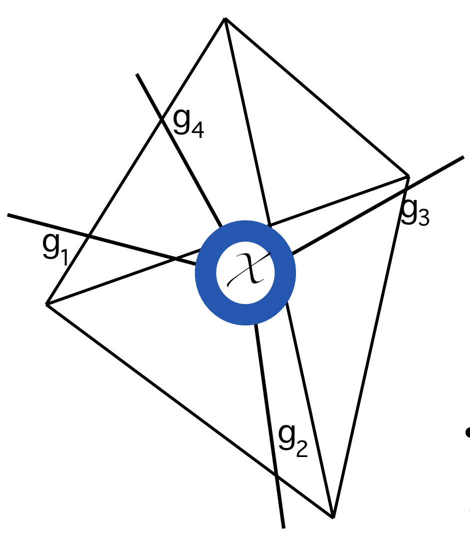
extension to TGFT models including "matter" dofs - example: scalar matter



basic guideline for model-building (choosing GFT action):

GFT Feynman amplitudes = simplicial path integrals for gravity coupled to scalar fields

- domain of GFT field extended to include values of scalar fields $\quad \hat{\varphi}(g_I, \chi^a) \equiv \hat{\varphi}(g_I, \chi^1, \ldots, \chi^n)$

with consequent extension of field operators, quantum states and operators on Fock space

and consequent extension of GFT action & eqns of motion

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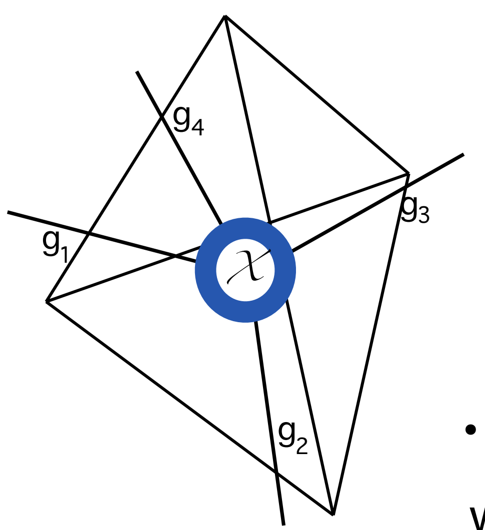

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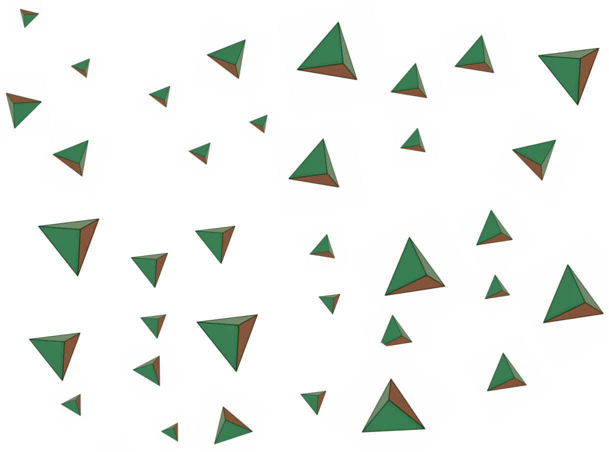
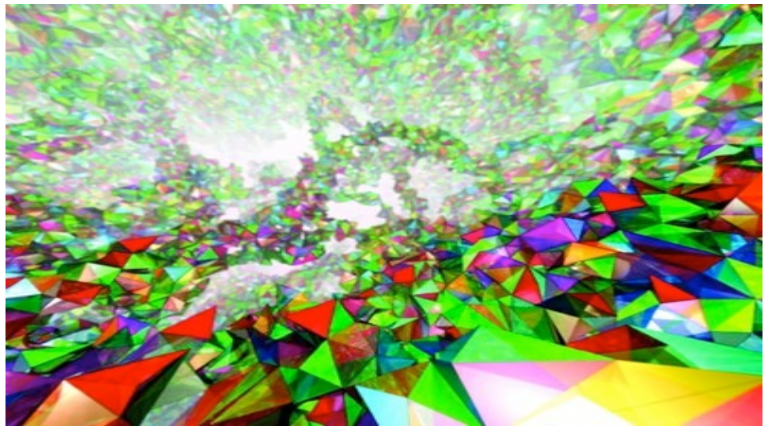
and consequent extension of GFT action & eqns of motion

$\longrightarrow$ Quantum Gravity as sum over simplicial topologies and over quantum discrete geometries

Emergent cosmological dynamics and field theory

M. Assanioussi, G. Calcagni, A. Calcinari, M. De Cesare, R. Dekhil, Delhom, F. Gerhardt, S. Gielen, F. Greco, A. Jercher, T. Landstaetter, I. Kotecha, S. Liberati, L. Marchetti, L. Mickel, DO, X. Pang, A. Pithis, A. Polaczek, M. Sakellariadou, L. Sindoni, A. Tomov, Y. Wang, E. Wilson-Ewing, ...


Continuum approximation and collective physics

TGFTs: field theories of quantized simplices with non-local interactions (describing how simplices form higher-cells)

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(universe as QG fluid)

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+ FRG analysis of simpler TGFT models

Gaussian critical point in "IR" (i.e. small-j), fluctuations suppressed, condensate phase

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$$F_\lambda(J) \;=\; \ln Z_\lambda[J] \qquad \Gamma[\phi] \;=\; sup_J\left(J\cdot\phi - F(J)\right) \qquad \langle\varphi\rangle = \phi$$

✳ simplest approximation: mean field hydrodynamics

$$\Gamma[\phi] \;\approx\; S_\lambda(\phi)$$

mean field ~ condensate wavefunction

- corresponding quantum states:

(simplest): GFT condensate, GFT field coherent state

$$|\sigma\rangle := \exp\left(\hat{\sigma}\right)|0\rangle$$

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Universe as BEC (TGFT condensate)

key features of GFT mean field hydrodynamics

- condensate wavefunction / mean field defined on minisuperspace

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  Gielen, '15

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$$\sigma(\mathcal{D}) \qquad \mathcal{D} \simeq \{\text{geometries of tetrahedron}\} \simeq$$
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general form of resulting (Gross-Pitaevskii) equations of motion for condensate wavefunction (mean field):

$$\int [dg']d\chi'\mathcal{K}(g,\chi;g',\chi')\sigma(g',\chi') + \lambda\frac{\delta}{\delta\varphi}\mathcal{V}(\varphi)|_{\varphi\equiv\sigma} = 0$$

polynomial functional of condensate wavefunction

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(domain extended to include scalar matter)

- can be extracted for any concrete TGFT model

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- what interactions capture:

more details of dynamics of quantum geometry, inhomogeneities, topology change

Hydrodynamics on (mini)superspace

- domain:

minisuperspace - geometric data (scale factors, often taking discrete (eigen)values) + (scalar) matter field values

$$\{\{a_i\}\ ,\ \{\phi\}\ ,\ ....\ ,\{\chi\}\} \qquad V \equiv V_0 a^3$$

metric manifold with minisuperspace metric

in QG context: $a \propto a_p j \qquad j = 0, 1/2, 1, ...$

- dynamical variable: (condensate) wavefunction on (mini)superspace ~ fluid density and phase

$$\Psi(a_i, \phi, .., \chi) = \rho(a_i, \phi, .., \chi) e^{i\,\theta(a_i, \phi, .., \chi)} \ \in\ \mathbb{C}$$

- general form of the action (example: single scalar field direction, single dynamical interaction term):

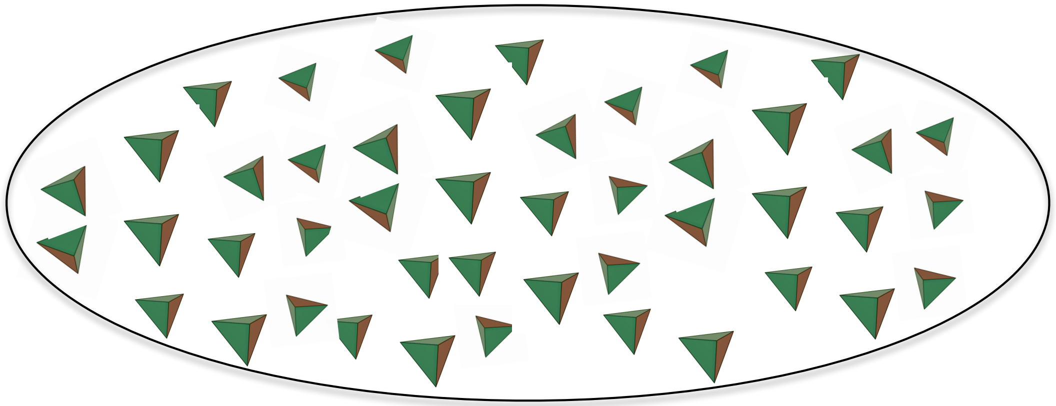
$$S = \int [da_i] d\phi\ \Psi^*(a_i, \phi)\, \mathcal{K}(a, \partial_{a_i}, \phi, \partial_\phi)\, \Psi(a_i, \phi) + \mathcal{V}[\Psi(a_i, \phi)]$$

non-linear extension of quantum cosmology! in general, non-local interaction on minisuperspace

- general form of eqns of motion (example: single scalar field direction, single dynamical interaction term):

$$\boxed{\begin{aligned} &\mathcal{K}\left(a, \partial_a, \phi, \partial_\phi\right) \Psi(a, \phi) + \frac{\delta}{\delta \Psi} \mathcal{V}\left[\Psi(a, \phi)\right] = \\ &= \mathcal{K}\Psi(a, \phi) + \lambda \int V\left(a_1, \partial_{a_1}, \phi_1, \partial_{\phi_1}; ....; a_n, \partial_{a_n}, \phi_n, \partial_{\phi_n}\right) \Psi(a_1, \phi_1) \cdots \Psi(a_{n-1}, \phi_{n-1}) = 0 \end{aligned}}$$

TGFT



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mean field approx

(coarse graining)

universe as QG condensate

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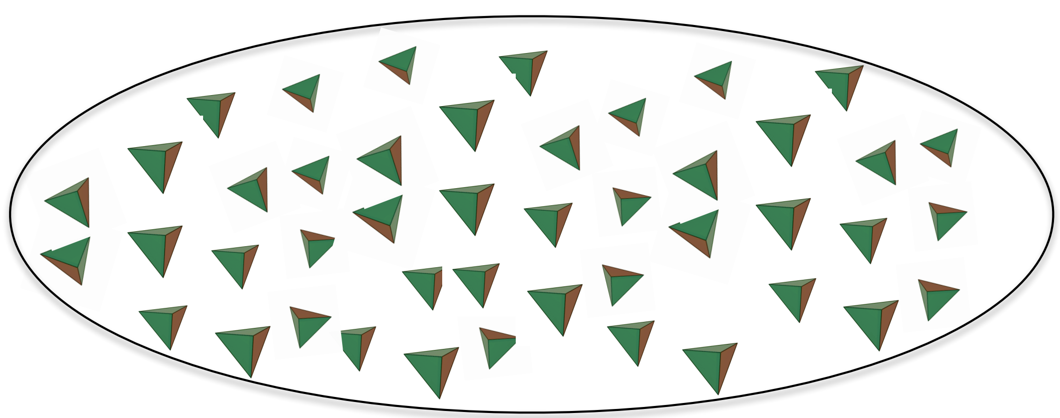

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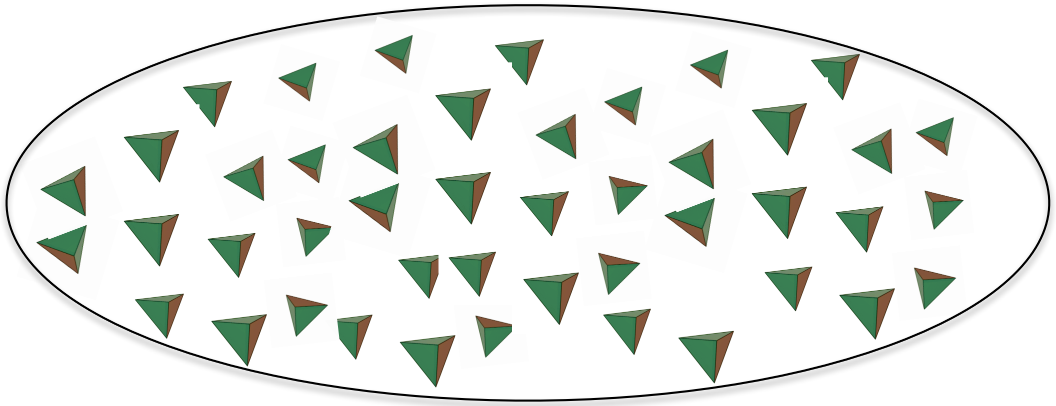

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$\sigma(a, \phi)$ "wavefunction" on minisuperspace

$$\mathcal{K}(a, \partial_a, \phi, \partial_\phi)\sigma(a, \phi) + \mathcal{V}'[\sigma(a, \phi)] = 0$$

hydrodynamic (non-linear, possibly non-local) eqn on minisuperspace

~ non-linear (loop) quantum cosmology

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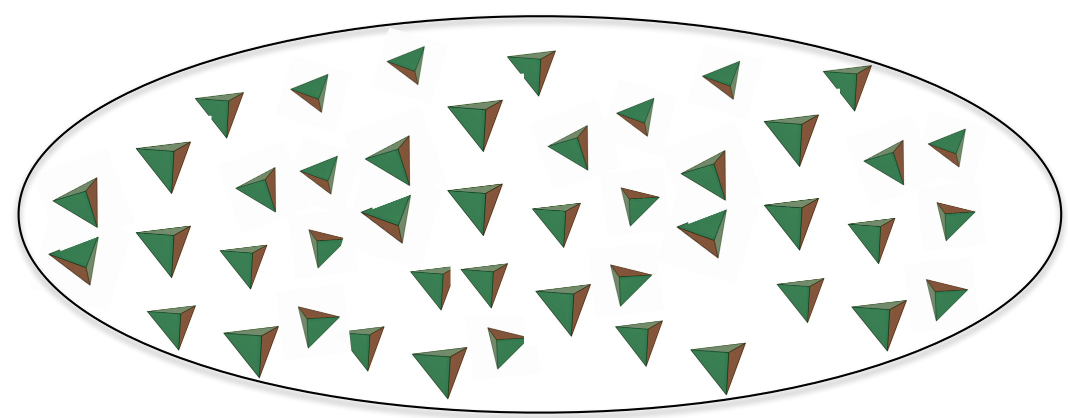

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correspondence based on:

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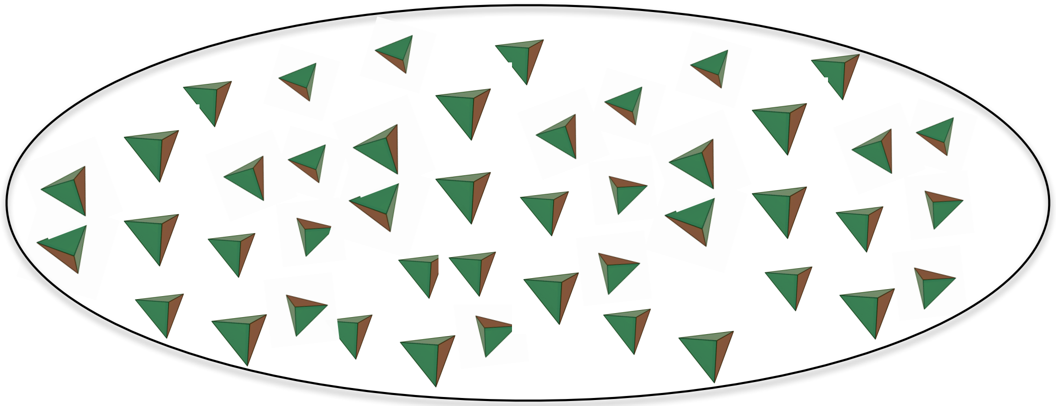

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quantum geometric model with 4 scalar dofs (1 clock+ 3 rods + 1 matter scalar field)

$$S_{\text{GFT}} = K + U + U^*$$

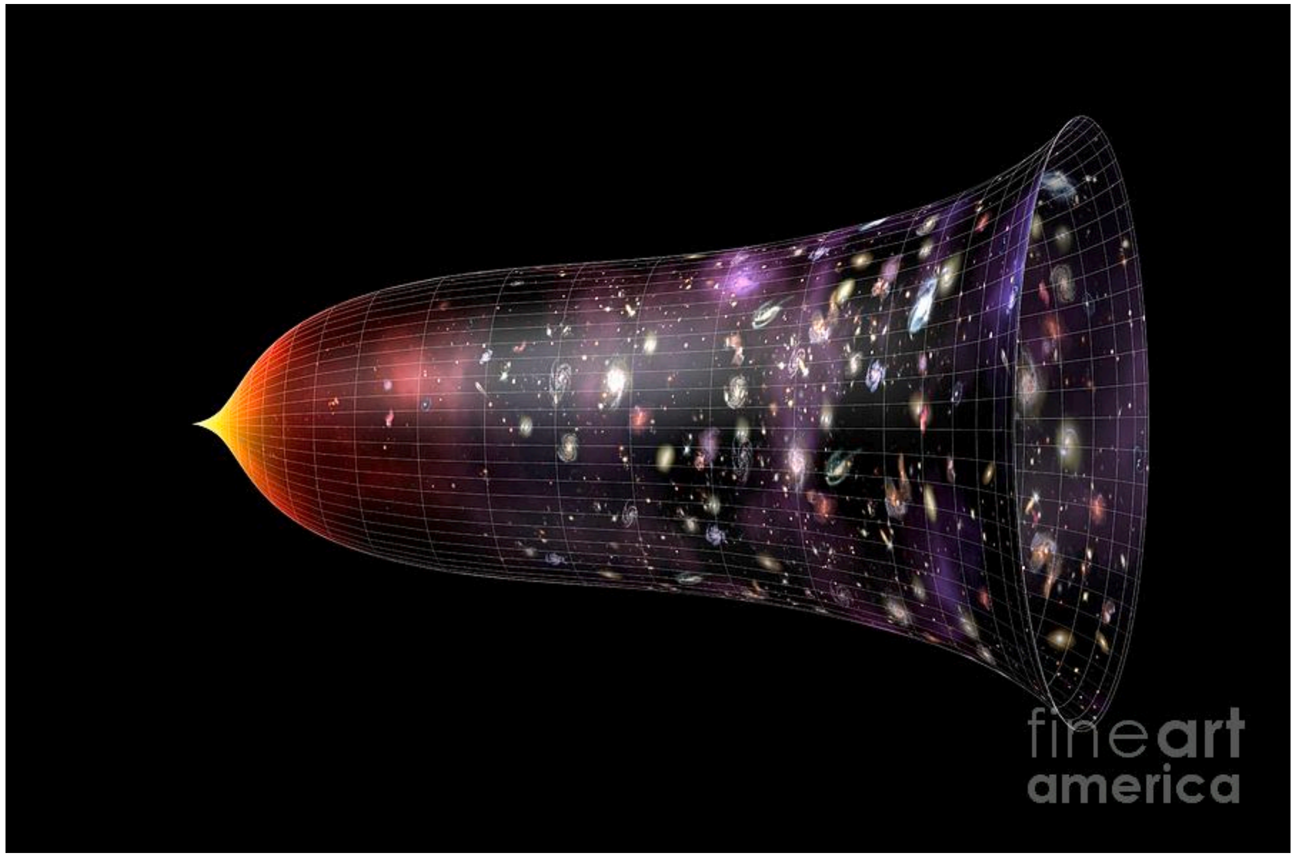
$$K = \int \mathrm{d}g_I \, \mathrm{d}h_I \int \mathrm{d}^d\chi \, \mathrm{d}^d\chi' \, \mathrm{d}\phi \, \mathrm{d}\phi' \, \bar{\varphi}(g_I, \chi) \mathcal{K}(g_I, h_I; (\chi - \chi')^2_\lambda, (\phi - \phi')^2) \varphi(h_I, (\chi')^\mu, \phi')$$

$$U = \int \mathrm{d}^d\chi \, \mathrm{d}\phi \int \left(\prod_{a=1}^{5} \mathrm{d}g_I^a \right) \mathcal{U}(g_I^1, \ldots, g_I^5) \prod_{\ell=1}^{5} \varphi(g_I^\ell, \chi^\mu, \phi)$$

next steps in construction of effective cosmological dynamics

from mean field hydrodynamics

to cosmological dynamics



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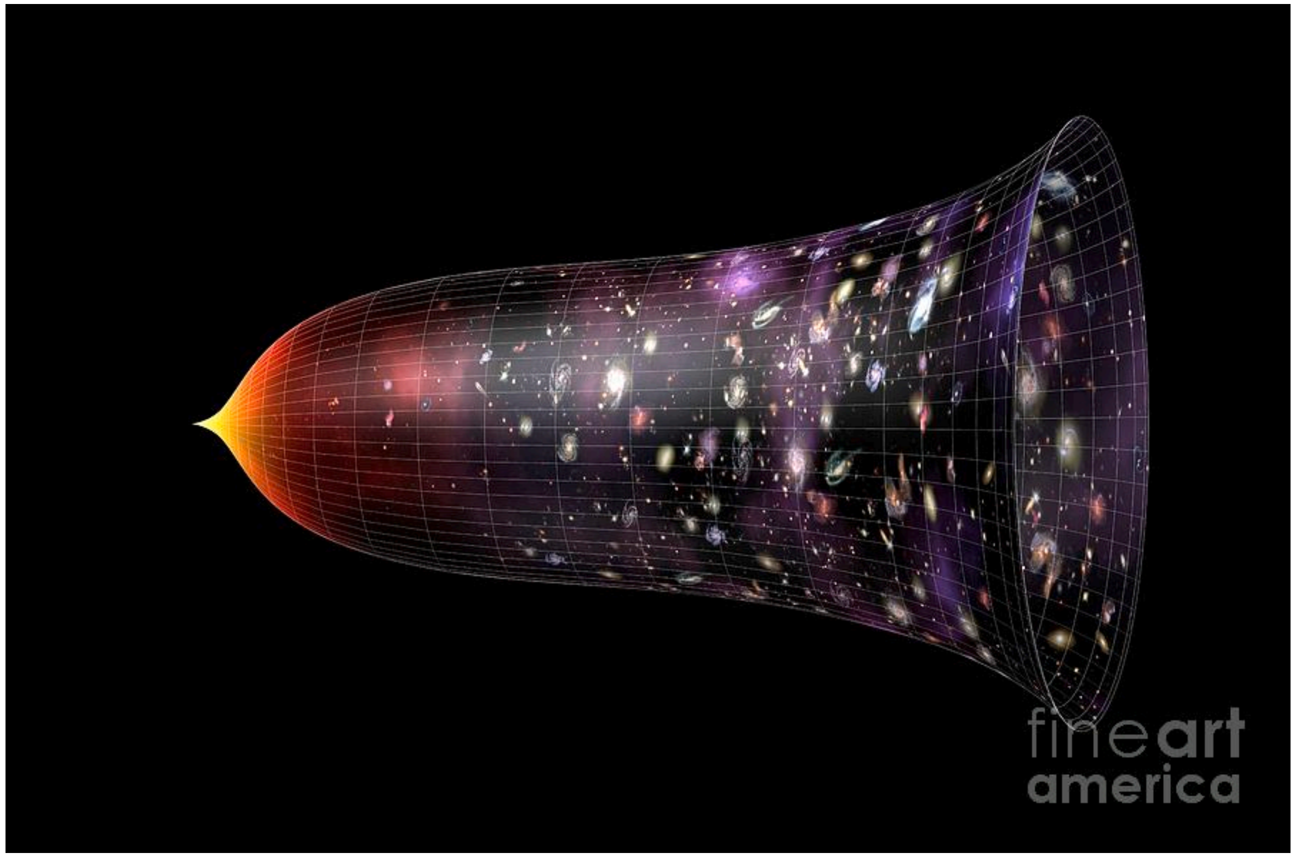

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restriction to "good clock+rods" condensate states - peakedness properties on clock/rod values

peaked functions (e.g. Gaussians)

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L. Marchetti, DO, '20, '21

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resulting (free) mean field hydrodynamics eqn:

Fourier mode of matter field variable

$$\partial_0^2\tilde{\sigma}_j(x,\pi_\phi) - i\gamma\partial_0\tilde{\sigma}_j(x,\pi_\phi) - {}^{(\lambda)}E_j^2(\pi_\phi)\tilde{\sigma}_j(x,\pi_\phi) + \alpha^2\nabla^2\tilde{\sigma}_j(x,\pi_\phi) = 0$$

Note: general kinetic term approximated to 2nd order derivatives wrt clock/rods, due to peaking functions

with $\alpha^2 \equiv \frac{1}{3}\frac{\delta z^2}{\epsilon z_0^2}$ (function of peaking parameters)

using: $\tilde{\sigma}_j \equiv \rho_j \exp[i\theta_j]$ rewrite in standard hydrodynamic form (fluid density, phase)

homogeneous background + inhomogeneous perturbations (spacetime localization defined in relational terms)

$$\rho_j = \bar{\rho}_j + \delta\rho_j \qquad \theta_j \equiv \bar{\theta}_j + \delta\theta_j \qquad \bar{\rho} = \bar{\rho}(x^0, \pi_\phi) \qquad \bar{\theta} = \bar{\theta}(x^0, \pi_\phi)$$

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$\longrightarrow$

background eqns:

$$\bar{\rho}_j''(x^0, \pi_\phi) - \left[\left(\bar{\theta}_j'(x^0, \pi_\phi)\right)^2 + {}^{(\lambda)}\eta_j^2(\pi_\phi) - \gamma\bar{\theta}_j'(x^0, \pi_\phi)\right]\bar{\rho}_j(x^0, \pi_\phi) = 0$$

$$\bar{\theta}_j''(x^0, \pi_\phi) + (\bar{\theta}_j'(x^0, \pi_\phi) - \gamma/2)\frac{(\bar{\rho}_j^2)'(x^0, \pi_\phi)}{\bar{\rho}_j^2(x^0, \pi_\phi)} - {}^{(\lambda)}\beta_j^2 = 0$$

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→ perturbations eqns: eg for large N (late time) and specific range of parameters

$$0 \simeq \delta\rho_j''(x, \pi_\phi) + \mathrm{Re}\,\alpha\nabla^2\delta\rho_j(x, \pi_\phi) - {}^{(\lambda)}\eta_j^2(\pi_\phi)\delta\rho_j(x, \pi_\phi)\,,$$

$$0 \simeq \delta\theta_j''(x, \pi_\phi) + 2\delta\theta_j'(x, \pi_\phi)\frac{\bar{\rho}_j'(x^0, \pi_\phi)}{\bar{\rho}_j(x^0, \pi_\phi)} + \mathrm{Re}\,\alpha\nabla^2\delta\theta_j(x, \pi_\phi)$$

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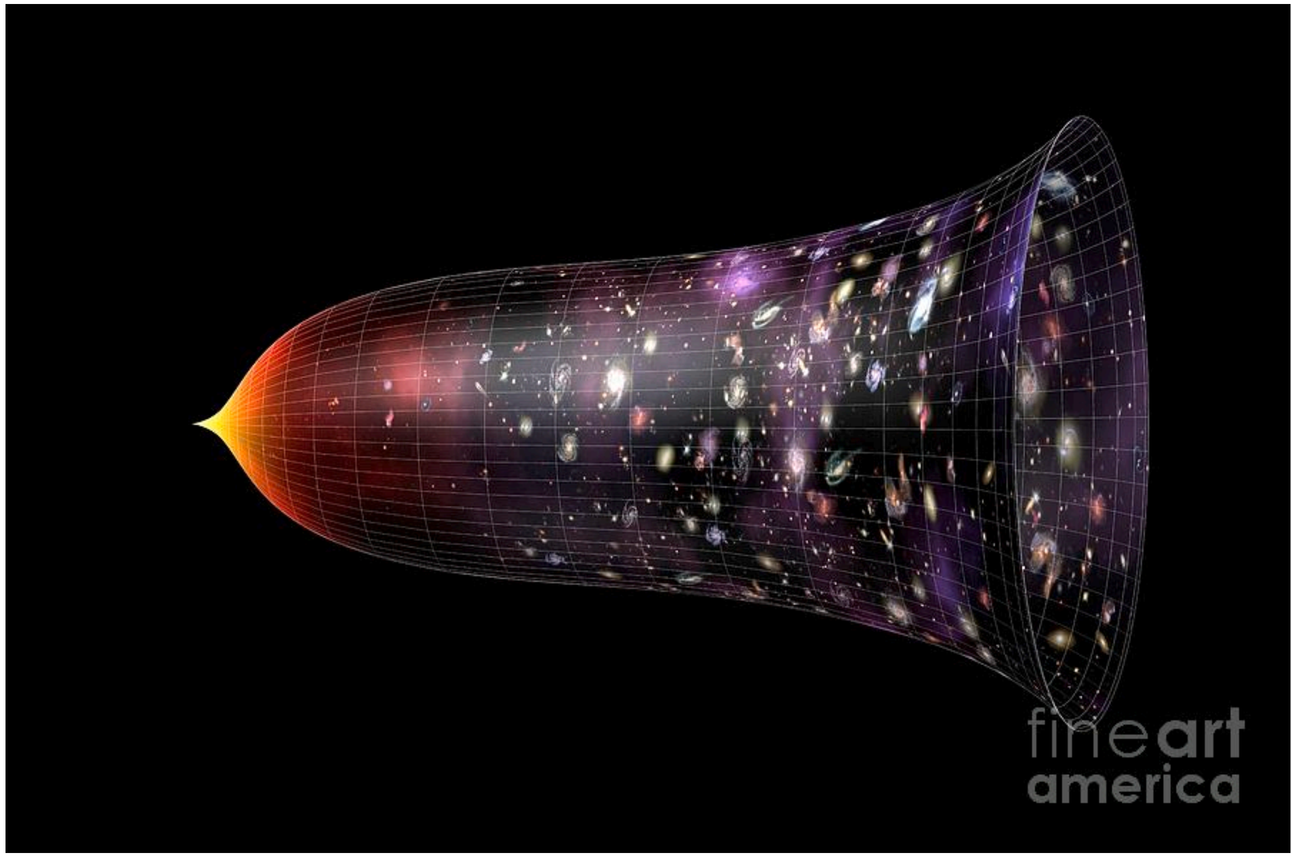

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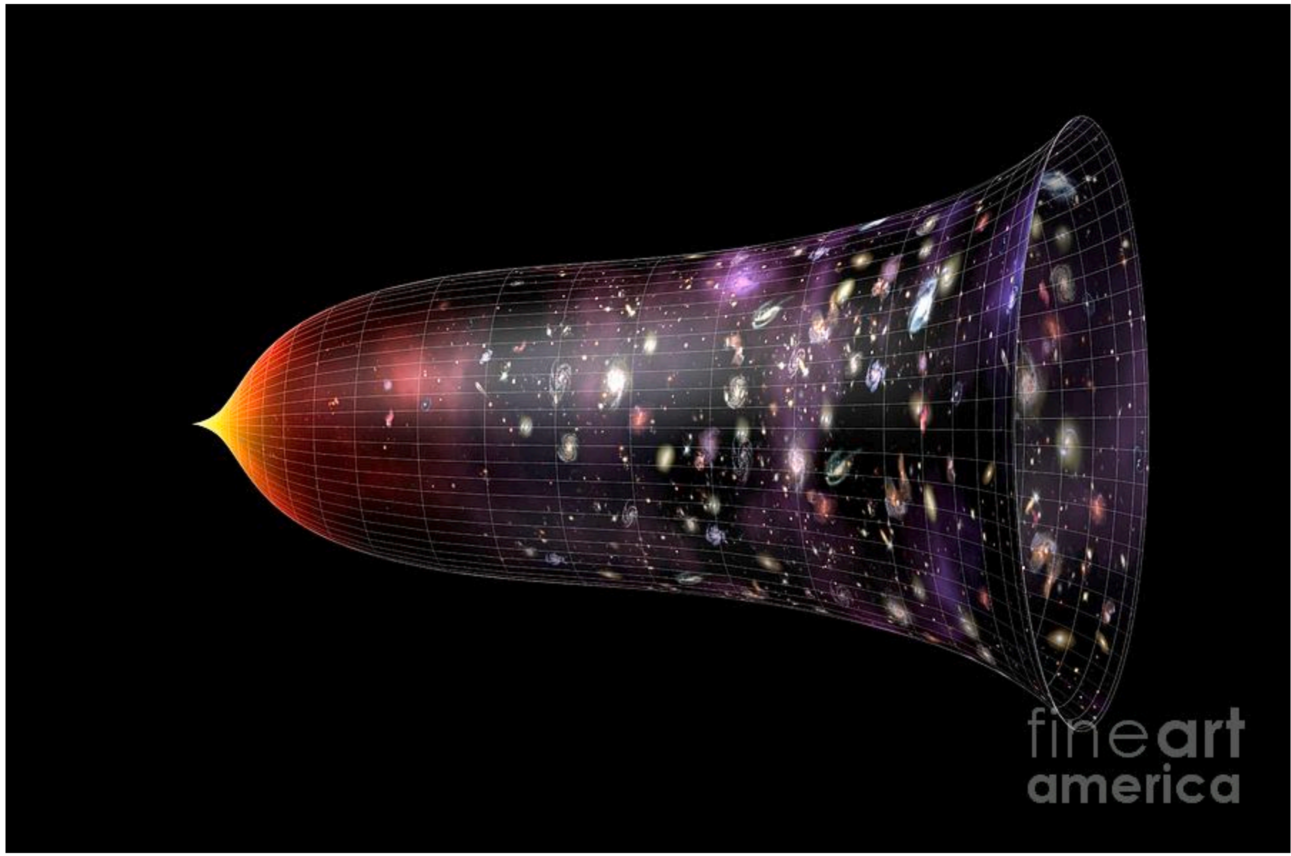
- turning relational hydrodynamics to dynamics of relational observables

example:

$$\left(\frac{V'}{V}\right)^2 = H^2 = f(V, \phi, \varphi, \sigma, ...)$$



next steps in construction of effective cosmological dynamics

from quantum GFT observables (defined on fundamental Fock space)

to relational cosmological quantities (few observables so far)

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$$O(\sigma) = \langle \sigma | \widehat{O} | \sigma \rangle$$

e.g.

$$\widehat{V} = \sum_j \int d\phi \, \varphi_j^\dagger(\phi) j^{3/2} \varphi_j(\phi)$$

- "particle" number $$N = \sum_j \int d\phi \, \sigma_j^*(\phi) \, \sigma_j(\phi)$$
- universe volume $$V = a_p^3 \sum_j \int d\phi \, \sigma_j^*(\phi) \, j^3 \sigma_j(\phi)$$
- value of matter scalar field $$\Phi = \sum_j \int d\phi \, \sigma_j^*(\phi) \, \phi \, \sigma_j(\phi)$$
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- going relational - to obtain relational time evolution:

choose one of scalar field variables in domain as "clock" - use it label evolution

- effective approach:

peaked condensate wavefunctions: $\sigma_\epsilon(j,\phi) \equiv \eta_\epsilon(j, \phi - \phi_0; \pi_0)\, \tilde{\sigma}(j,\phi)$

other approaches
A. Calcinari, S. Gielen, E. Wilson-Ewing, ...

peaking function around ϕ_0
with a typical width given by $\epsilon \ll 1$

fluctuations in (conjugate) scalar field momentum also small if: $\epsilon\pi_0^2 \gg 1$

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- effective relational observables (localized "at given moment in time"):

$$N(\phi_0)\,,\; V(\phi_0)\,,\; \Phi(\phi_0) \simeq \phi_0\,,\; \Pi_\phi(\phi_0)$$

using: $\tilde{\sigma}_j \equiv \rho_j \exp[i\theta_j]$ rewrite in standard hydrodynamic form (fluid density, phase)

homogeneous background + inhomogeneous perturbations (spacetime localization defined in relational terms)

$$\rho_j = \bar{\rho}_j + \delta\rho_j \qquad \theta_j \equiv \bar{\theta}_j + \delta\theta_j \qquad \bar{\rho} = \bar{\rho}(x^0, \pi_\phi) \qquad \bar{\theta} = \bar{\theta}(x^0, \pi_\phi)$$

→ background eqns:

$$\bar{\rho}_j''(x^0, \pi_\phi) - \left[\left(\bar{\theta}_j'(x^0, \pi_\phi)\right)^2 + {}^{(\lambda)}\eta_j^2(\pi_\phi) - \gamma\bar{\theta}_j'(x^0, \pi_\phi)\right] \bar{\rho}_j(x^0, \pi_\phi) = 0$$

$$\bar{\theta}_j''(x^0, \pi_\phi) + (\bar{\theta}_j'(x^0, \pi_\phi) - \gamma/2)\frac{(\bar{\rho}_j^2)'(x^0, \pi_\phi)}{\bar{\rho}_j^2(x^0, \pi_\phi)} - {}^{(\lambda)}\beta_j^2 = 0$$

→ perturbations eqns: eg for large N (late time) and specific range of parameters

$$0 \simeq \delta\rho_j''(x, \pi_\phi) + \mathrm{Re}\,\alpha\nabla^2\delta\rho_j(x, \pi_\phi) - {}^{(\lambda)}\eta_j^2(\pi_\phi)\delta\rho_j(x, \pi_\phi)\,,$$

$$0 \simeq \delta\theta_j''(x, \pi_\phi) + 2\delta\theta_j'(x, \pi_\phi)\frac{\bar{\rho}_j'(x^0, \pi_\phi)}{\bar{\rho}_j(x^0, \pi_\phi)} + \mathrm{Re}\,\alpha\nabla^2\delta\theta_j(x, \pi_\phi)$$

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from which we get eqns for observables

- expectation values of "microscopic observables" in peaked condensate states: relational spacetime-localized observables

$$N(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{N}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle \qquad V(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{V}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle$$

$$X^\mu(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{V}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle \simeq x^\mu \qquad \Pi(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\widehat{\Pi_\nu}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle$$

$$\phi(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\hat{\Phi}|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle \qquad \Pi_\phi(x^0,x^i) \equiv \langle\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}|\widehat{\Pi}_\phi|\sigma_{\epsilon,\delta,\pi_0,\pi_x,x^\mu}\rangle$$

quantities of interest for effective continuum gravitational physics emerge as coarse-grained, collective observables, averages in suitable class of QG states

by inserting dynamics of condensate background into expression for universe volume: background universe dynamics

background volume dynamics:

M. Assanioussi, G. Calcagni, A. Calcinari, M. De Cesare, G. Chirco, R. Dekhil, P. Fischer, F. Gerhardt, S. Gielen, F. Greco A. Jercher, I. Kotecha, T. Landstaetter, S. Liberati, L. Marchetti, DO, X. Pang, A. Pithis, A. Polaczek, M. Sakellariadou, L. Sindoni, A. Tomov, Y. Wang, E. Wilson-Ewing, ...

- intermediate times: large volume - QG interactions still subdominant

(here written neglecting matter contribution)

$$\boxed{\left(\frac{V'}{V}\right)^2 = \frac{V''}{V} = 12\pi\tilde{G}}$$

classical Friedmann dynamics in GR (wrt relational clock, with effective Newton constant) - flat FRW

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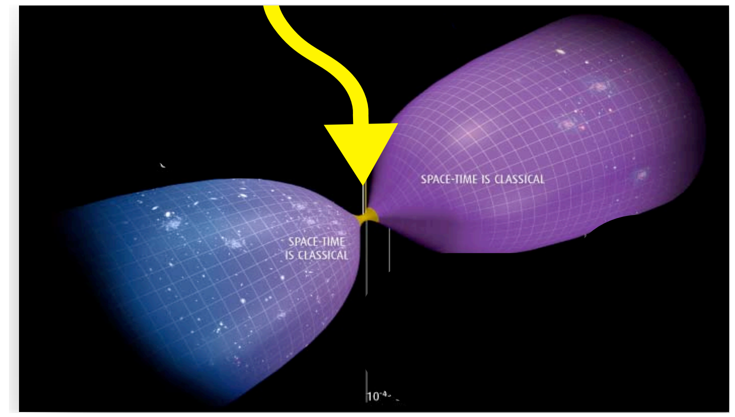
- very early times: very small volume - QG interactions subdominant

quantum bounce
(no big bang singularity)!



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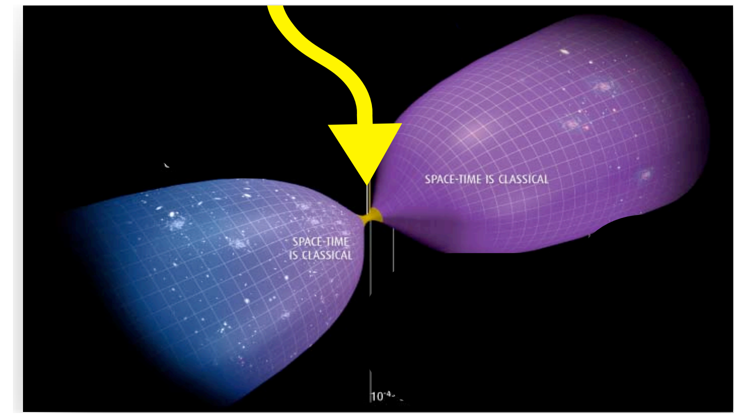

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$\longrightarrow$ accelerated cosmological expansion

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X. Pang, DO, '21

$\longrightarrow$ effective phantom-like dark energy (of pure QG origin)

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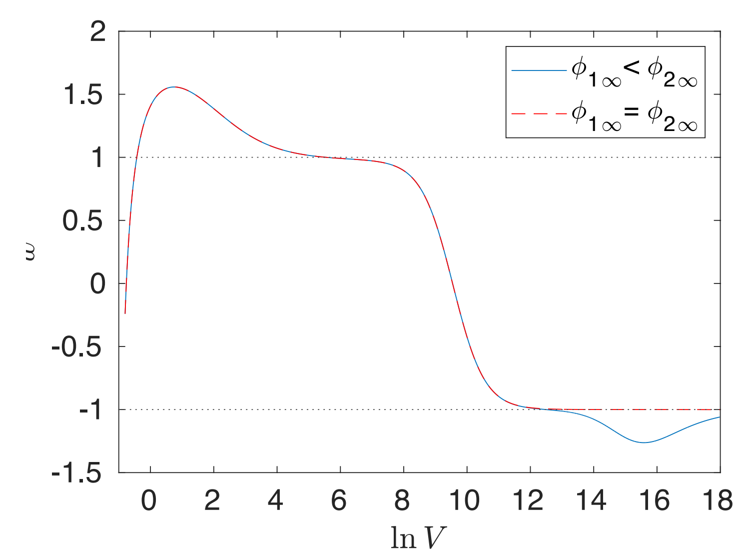

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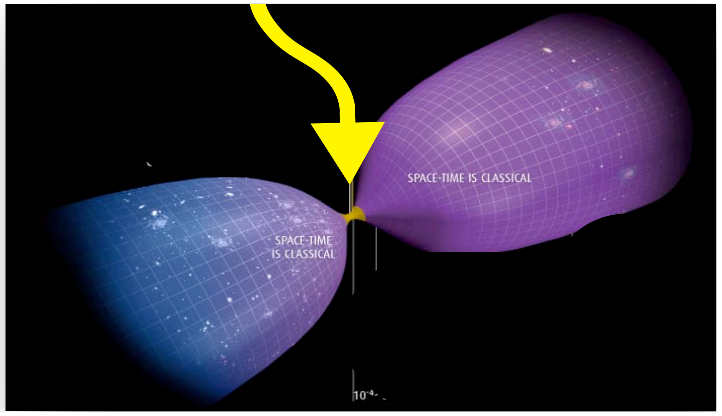

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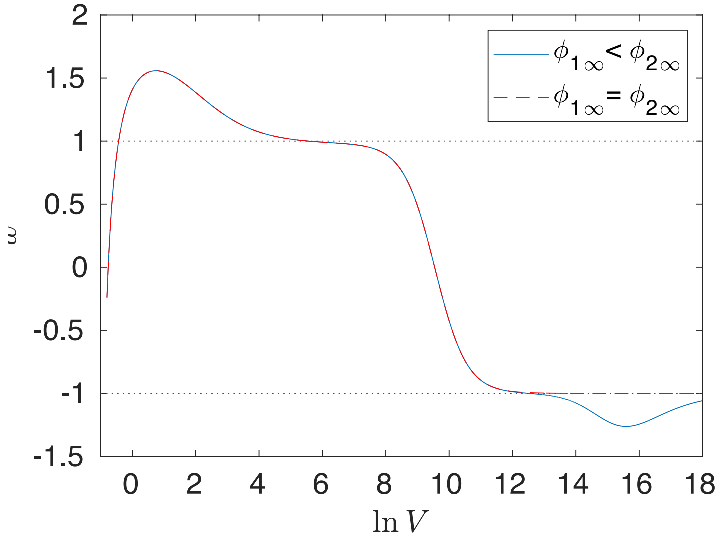

- QG-produced early-time acceleration possible

M. De Cesare, A. Pithis, M. Sakellariadou, '17; M. De Sousa, A. Barrau, K. Martineau, '23
T. Landstätter, L. Marchetti, DO, to appear

we can compute the dynamical eqns for volume and matter perturbations, using perturbed hydrodynamic eqns,

L. Marchetti, DO, '21

with identifications: $\phi = \langle \hat{\Phi} \rangle_\sigma \qquad \pi_\phi = \langle \hat{\Pi}_\phi \rangle_\sigma / \bar{N}$

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where correct Lorentzian signature is obtained if: $\mathrm{Re}\,\alpha^2 = \dfrac{\pi_x^2}{6\epsilon z_0^2}\left(\delta_r^2 - \delta_i^2\right) < 0$

and standard D'Alambertian is obtained for specific state parameters only

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L. Marchetti, DO, '21

- analysis for both background dynamics and effective volume/scalar perturbations can be extended to small-volume/early times regime

R. Dekhil, F. Greco, S. Liberati, DO, to appear

Further results

- correct GR dynamics of higher-momenta (but still sub-planckian) perturbations (volume and scalar field) can be recovered by extended construction, involving more details of discrete causal structure:

A. Jercher, L. Marchetti, A. Pithis, '23,'24

- extended TGFT with both timelike and spacelike fields (creating timelike and spacelike tetrahedra) with kinetic kernels:

$$\mathcal{K}_+ = \mathcal{K}_+\left(g_v, g_w; (\chi_v^0 - \chi_w^0)^2, (\phi_v - \phi_w)^2\right)$$

$$\mathcal{K}_- = \mathcal{K}_-\left(g_v, g_w; |\boldsymbol{\chi}_v - \boldsymbol{\chi}_w|^2, (\phi_v - \phi_w)^2\right)$$

(timelike/spacelike scalar frame components)

- extended TGFT condensate of both timelike and spacelike quantum tetrahedra (previously only spacelike ones)

$$\left|\Delta; x^0, \boldsymbol{x}\right\rangle = \mathcal{N}_\Delta e^{\hat{\sigma}\otimes\mathbb{1}_- + \mathbb{1}_+\otimes\hat{\tau} + \delta\hat{\Phi}\otimes\mathbb{1}_- + \delta\hat{\Psi} + \mathbb{1}_+\otimes\delta\hat{\Xi}} \left|\emptyset\right\rangle$$

key role of entanglement between timelike and spacelike components

- background dynamics unaffected (and matching GR at large volumes/late-times)

- dynamics of volume and scalar field perturbations at late times:

$$\left(\frac{\delta V}{\bar{V}}\right)'' + a^4k^2\left(\frac{\delta V}{\bar{V}}\right) = -3\mathcal{H}\left(\frac{\delta V}{\bar{V}}\right)' \qquad \delta\phi'' + a^4k^2\delta\phi = J_\phi$$

which match GR dynamics

with QG corrections (very small in sub-Planckian regime):

$$J_\phi = -c\left(\frac{a^2k}{M_{\mathrm{Pl}}}\right)\bar{\phi}'\left[-\frac{3}{\sqrt{6}}\bar{\phi} + 2M_{\mathrm{Pl}}\right]\Gamma\left(\frac{7}{4}\right) \times \left(\frac{4\mathcal{H}}{a^2k}\right)^{3/4} J_{7/4}\left(\frac{a^2k}{2\mathcal{H}}\right),$$

New emergent spacetime physics

- emergent cosmology with quantum bounce (in hydrodynamic approximation) L. Sindoni, DO, E. Wilson-Ewing, '16

- effective QG-inflation (with graceful exit) at early times T. Landstätter, L. Marchetti, DO, to appear

- corrections to GR dynamics due to physical frame (quantum clock&rods) L. Marchetti, DO, '20, '21

- fluctuations of quantum geometric (cosmological) observables L. Marchetti, DO, '20, '21

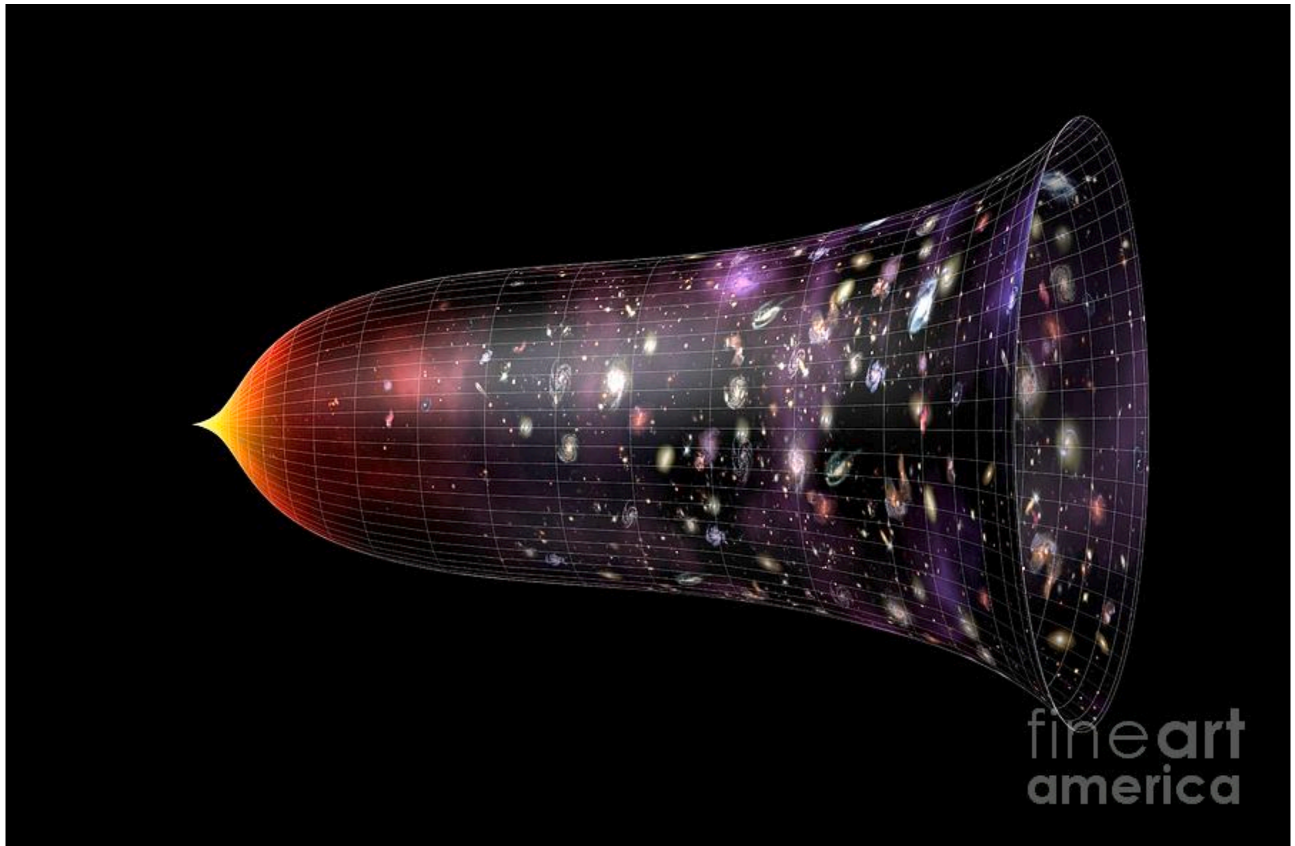
- emergent cosmological constant (asymptotic deSitter expansion), with value tied to parameters governing quantum bounce

  X. Pang, DO, '21, '25

  T. Landstätter, L. Marchetti, DO, to appear

- effective phantom-like dark energy dynamics from QG at late times

  X. Pang, DO, '21, '25



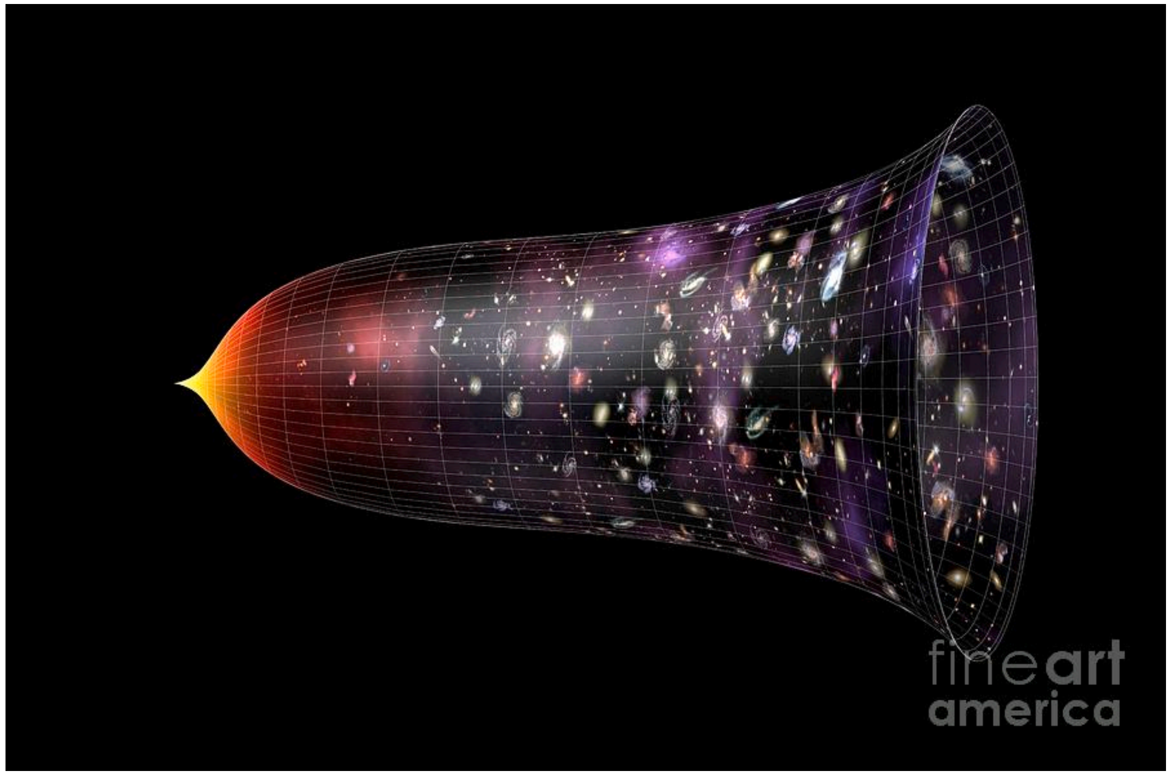
New emergent spacetime physics

- effective volume & scalar field dynamics (effective QFT) can be derived at both small-volume/early times (close to quantum bounce) regime and late times

R. Dekhil, F. Greco, S. Liberati, DO, to appear

  - very involved equations

  - include: effective potential/mass terms, dissipative terms, QG effects on background, ...



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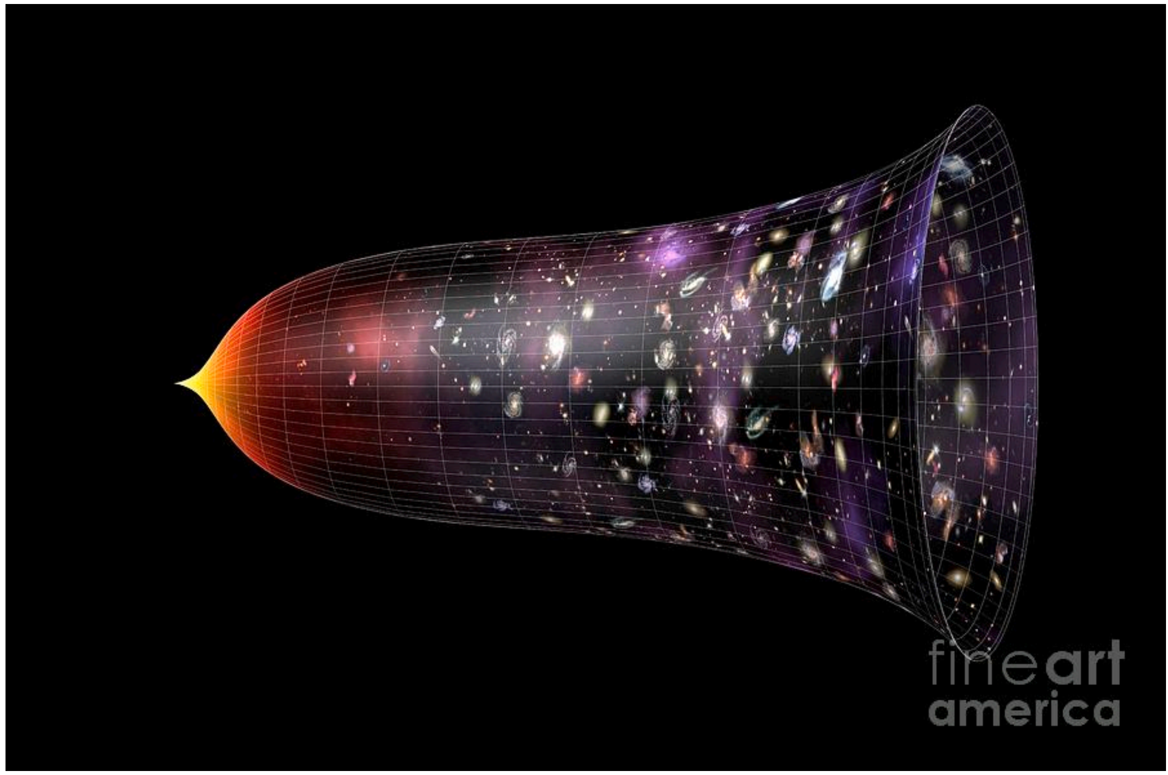

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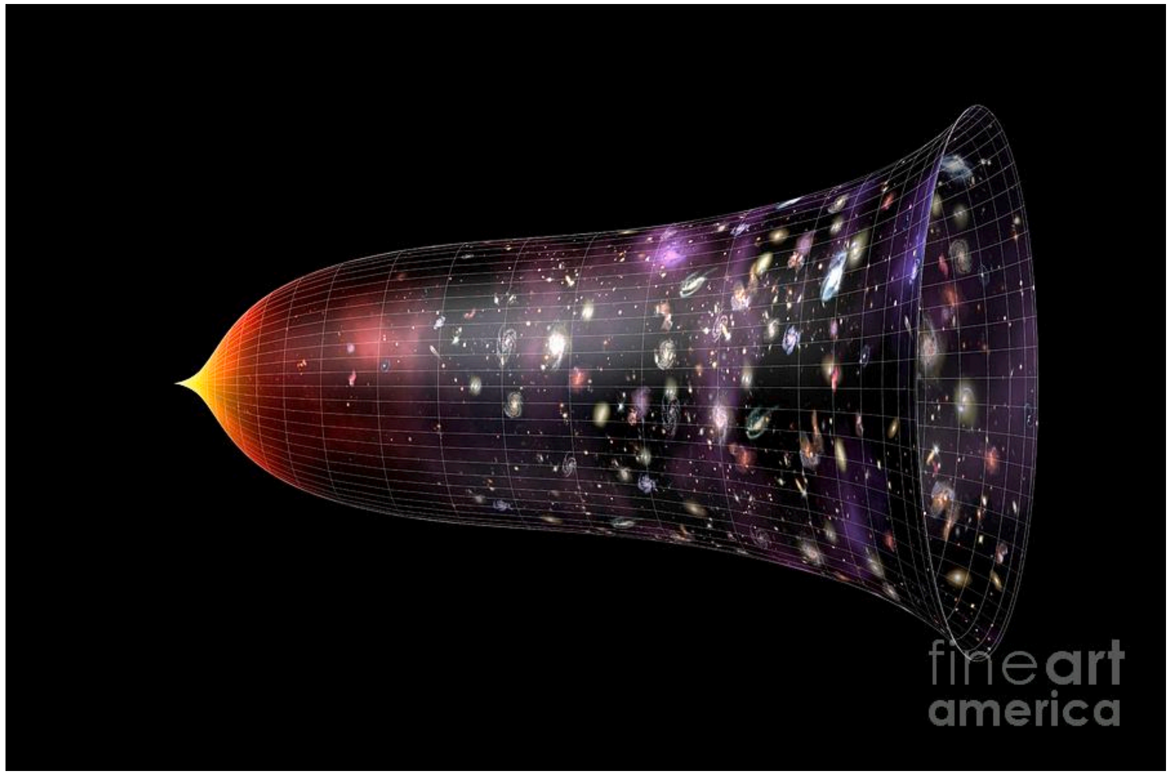
  - collective vacuum state
  - dynamical regime
  - properties of physical frame and relational strategy



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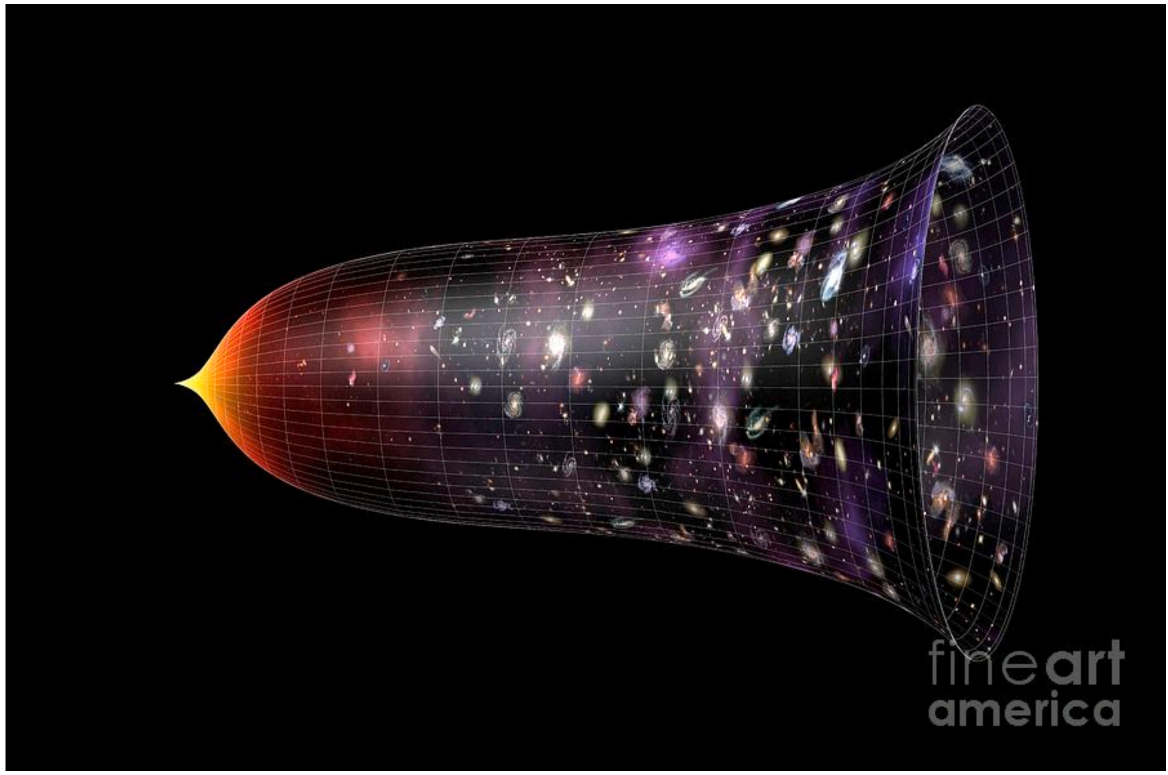

- corrections to standard QFT and GR come from
    - QG effects on background and perturbations dynamics
    - peaking properties (physical nature of matter frame)
    - corrections to mean field hydrodynamics approximation
    - ....

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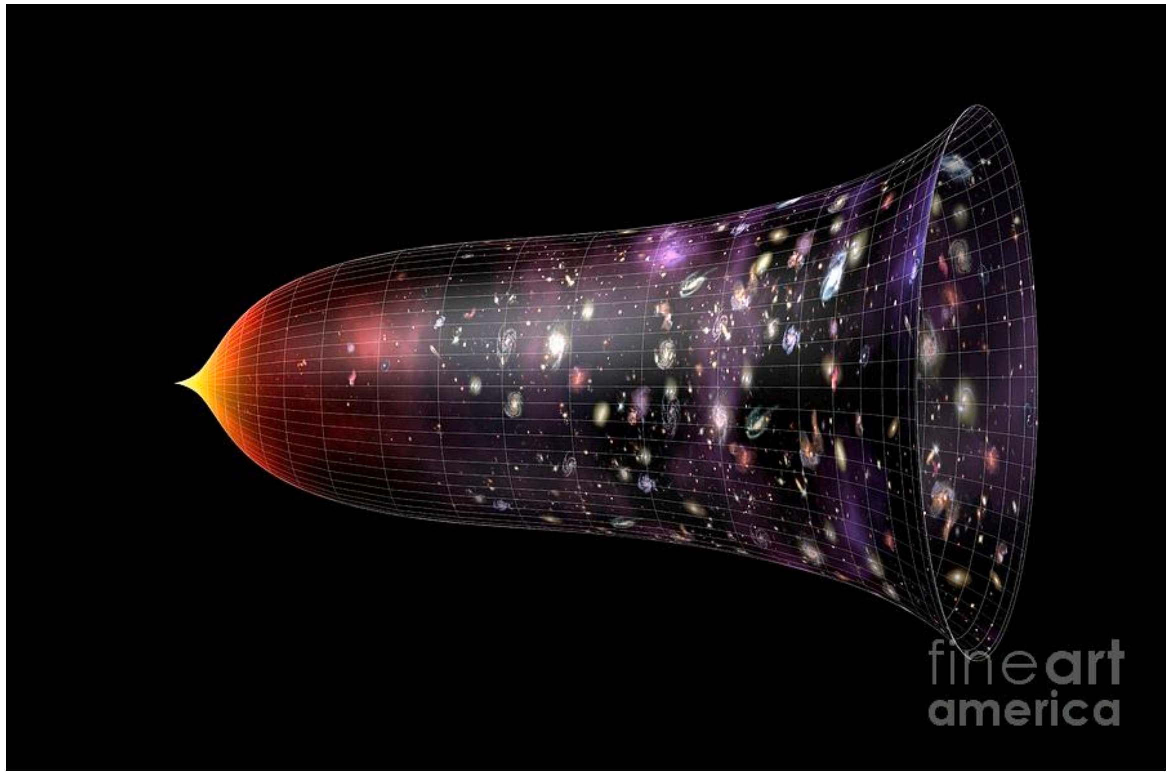
R. Dekhil, F. Greco, S. Liberati, DO, to appear

  - very involved equations
  - include: effective potential/mass terms, dissipative terms, QG effects on background, ...

- both geometry and matter are emergent/collective observables

- Lorentzian structure and symmetry recovered but, in general, depend on:
  - TGFT model
  - collective vacuum state
  - dynamical regime
  - properties of physical frame and relational strategy



- corrections to standard QFT and GR come from
  - QG effects on background and perturbations dynamics
  - peaking properties (physical nature of matter frame)
  - corrections to mean field hydrodynamics approximation
  - ....

    - most, if not all aspects of usual QFT, are approximate (unitarity, locality, ...)

Lessons, broader issues, further directions

1. Cosmology as hydrodynamic approximation of QG system: collective, coarse grained QG dynamics

- focus on cosmological dynamics = focus on few global, collective observables = (result of coarse graining
- cosmological wavefunction on minisuperspace = order parameter labelling collective state, not quantum state
  no corresponding Hilbert space of "quantum cosmology" within larger Hilbert space of QG states

$$\langle\Omega|\widehat{\varphi}|\Omega\rangle = \Psi(a,\phi) \qquad \Psi(a,\phi) \;=\; \rho(a,\phi)e^{i\theta(a,\phi)}$$

- relevant observables are matched with continuum gravitational physics as averages, not eigenvalues

3. Cosmological evolution is relational evolution with respect to physical clock

- relational evolution requires conditions of (good) clock, implemented as conditions on relevant quantum states
- which clock? possible mismatch between "fundamental" and "effective" clock dofs
  eg: "massless free scalar field" at fundamental level =/= massless free scalar field at effective (hydrodynamic) level

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2. Cosmology is emergent dynamics, taking form of non-linear extension of (loop) quantum cosmology

- dynamics of cosmological wavefunction = non-linear extension of LQC, i.e. QG hydrodynamics on minisuperspace

$$\mathcal{K}(a, \phi) \, \Psi(a, \phi) + \lambda_i \int \mathcal{V}(a_1, \phi_1; \ldots; a_i, \phi_i) \Psi(a_1, \phi_1) \cdots \Psi^*(a_i, \phi_i) = 0$$

- gravitational couplings (in emergent cosmological dynamics) are functions of QG ones (not directly gravitational)
- non-linear contributions important; example: in GFT can produce cosmic acceleration without additional dofs
- large-scale effects of direct QG origin and linked to small-scale effects (failure of EFT intuition and principles)

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$\Longrightarrow$ Most principles of QFT and GR are emergent & approximate (locality, unitarity, local causality, ...)

Physical (cosmological) significance of RG flow and phase transitions

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- If QG system leaves condensate (geometric) phase: e.g. quantum fluctuations drive quantum dynamics towards phase transition, QG system reaches criticality

→ even more radical disappearance of continuum spacetime

necessary: pre-geometric, non-spatiotemporal description in terms of QG “atoms" and full understanding of QG phase transition

DO, '07, '17

“geometrogenesis”

General covariance vs Physical covariance - how does physics depend on physical frames?

geometry + matter, not localized in spacetime (not functions of manifold points/directions nor of physical events,...)

(equivalence classes of metrics and matter fields under diffeos)

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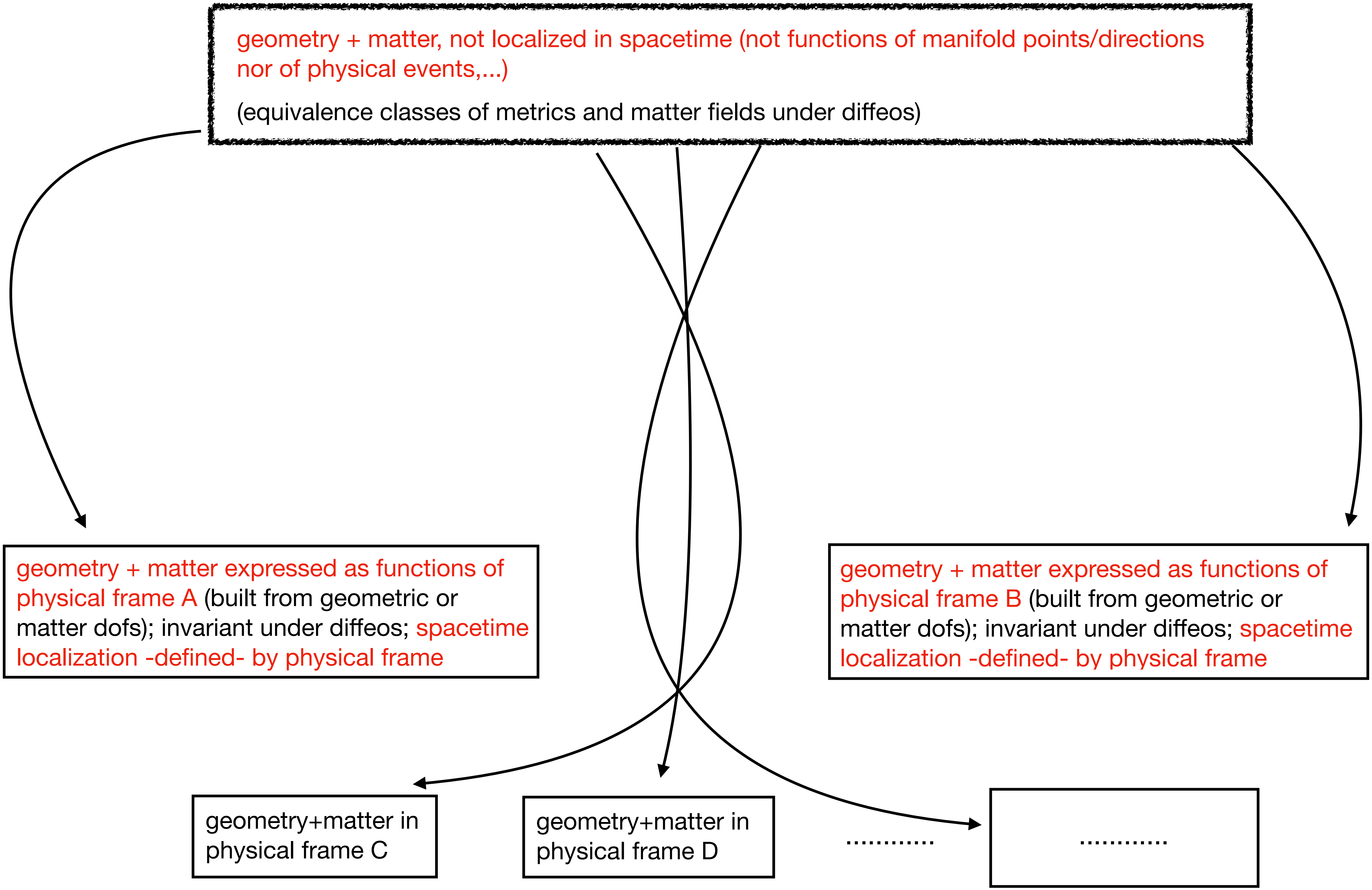

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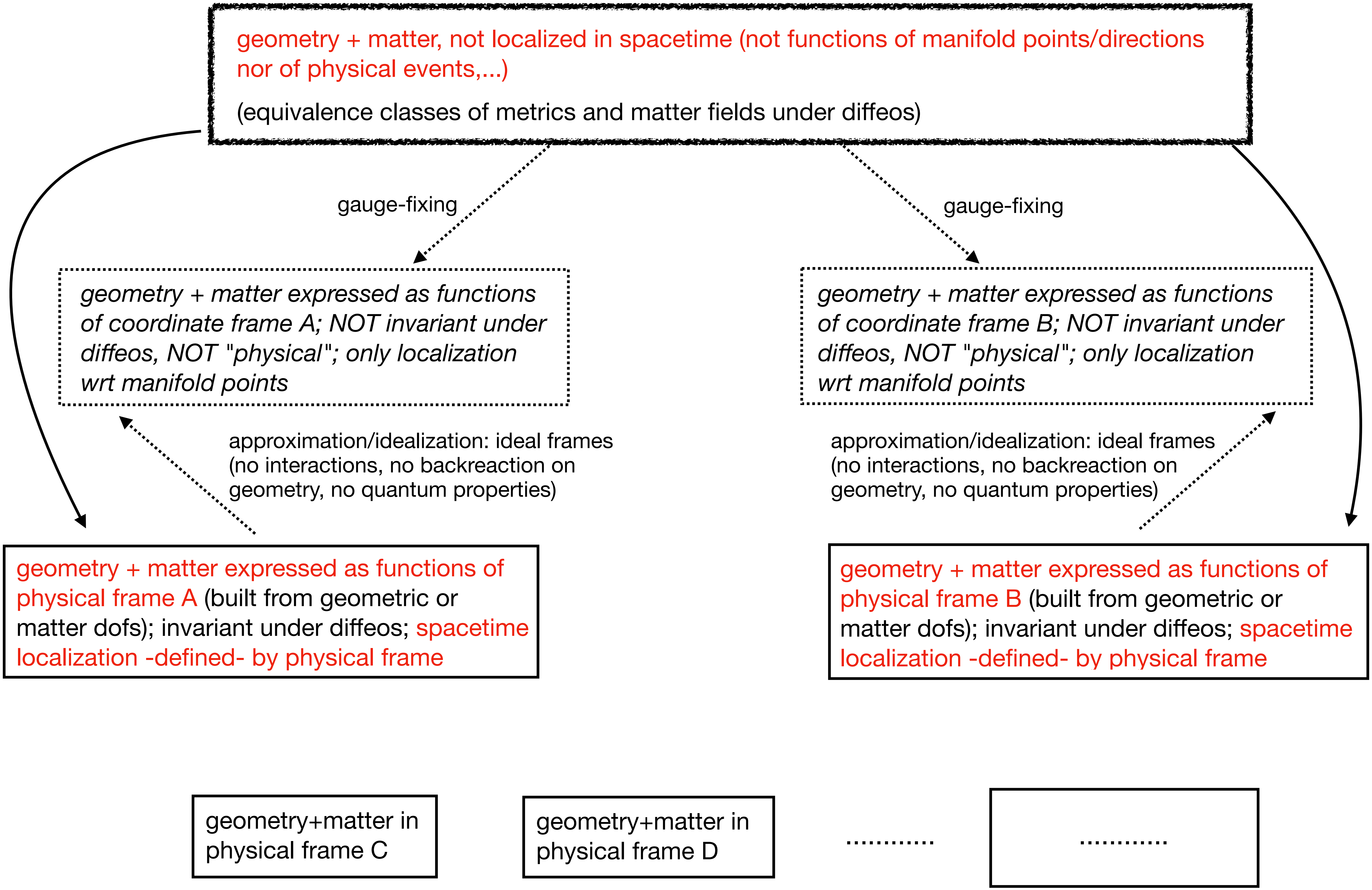

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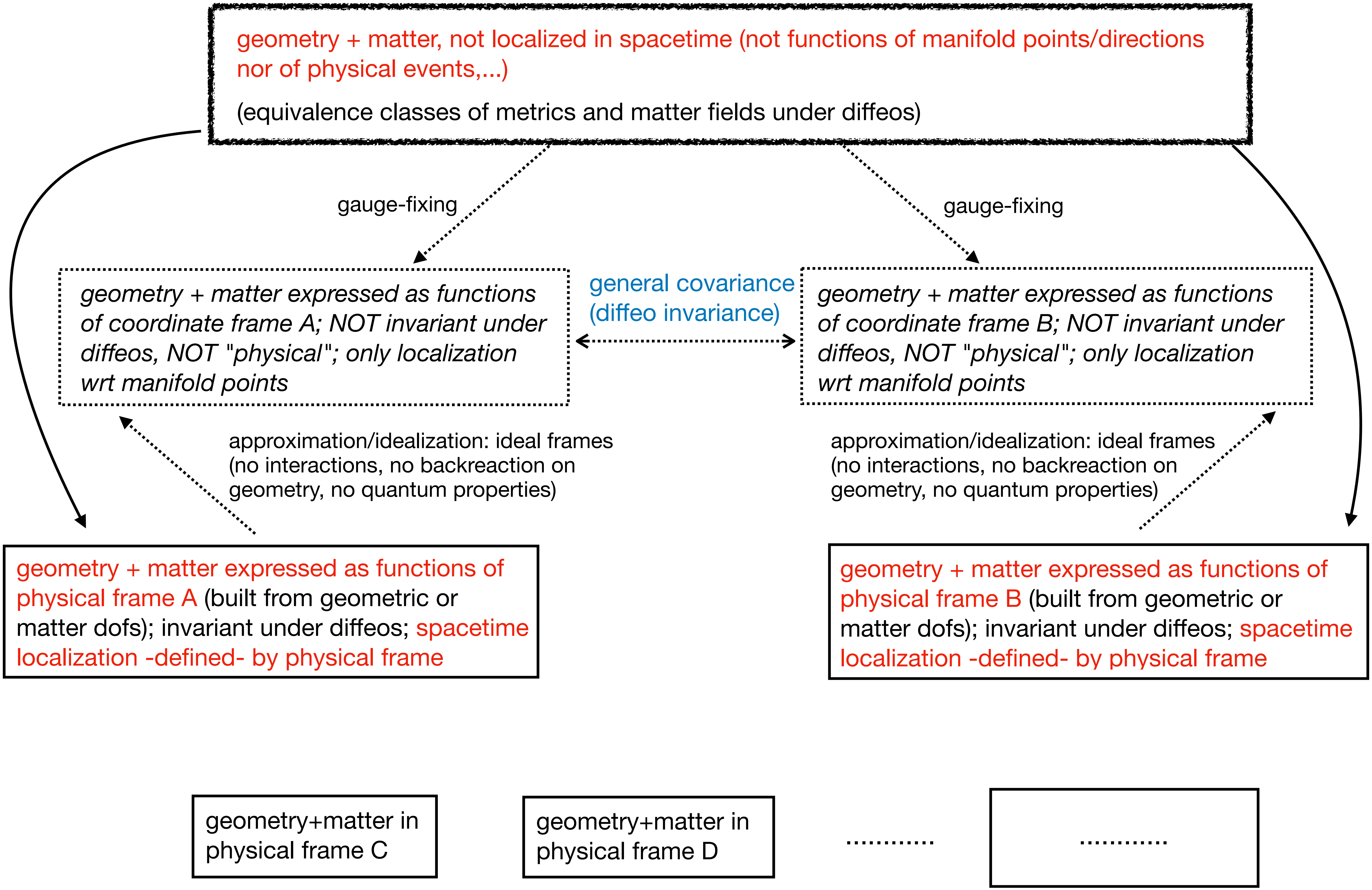

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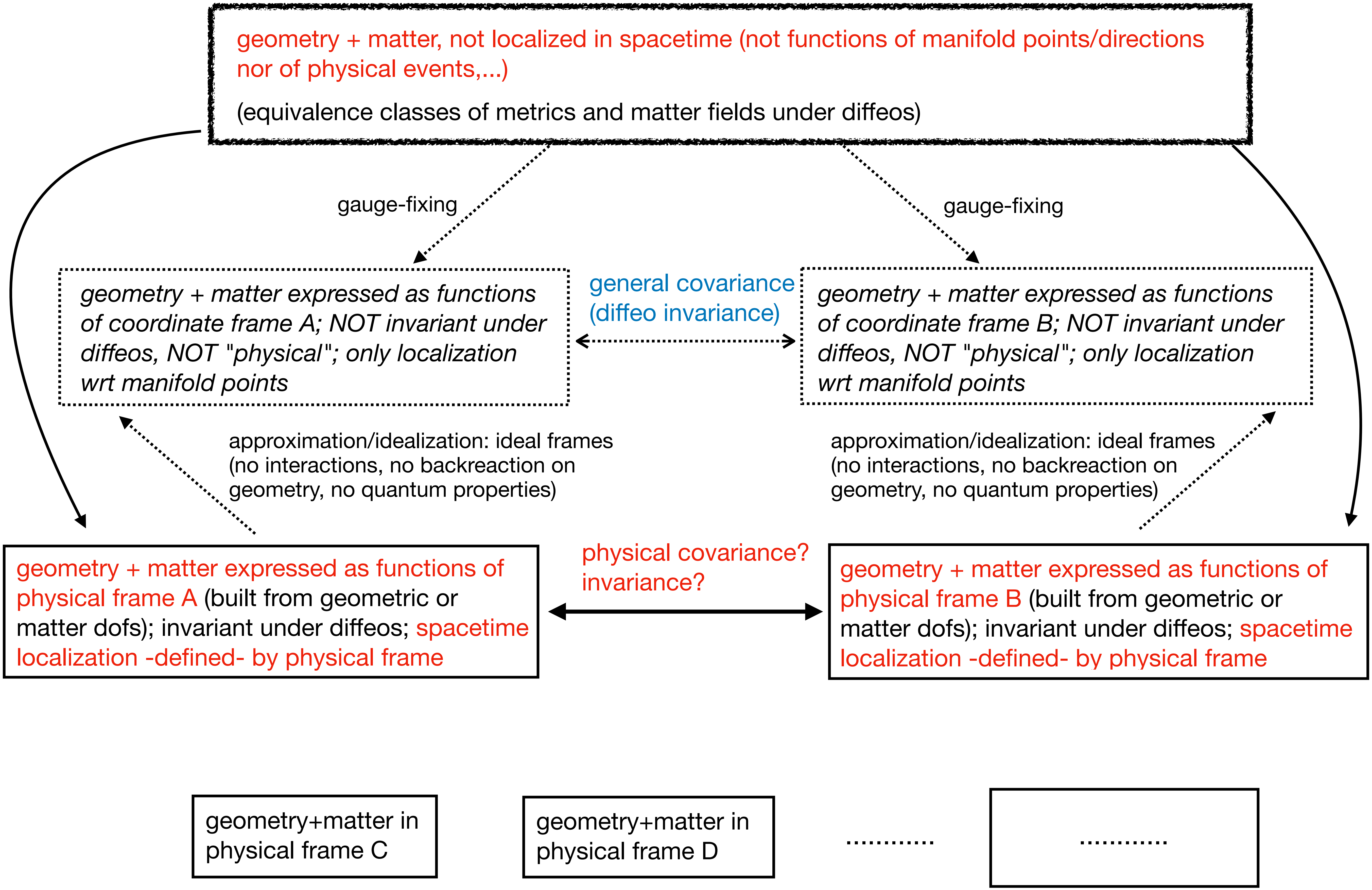

Quantum Gravity challenges to Laws

V. Lam, C. Wuthrich, '23

no spacetime challenge

kinematical structures in QG are not spatiotemporal

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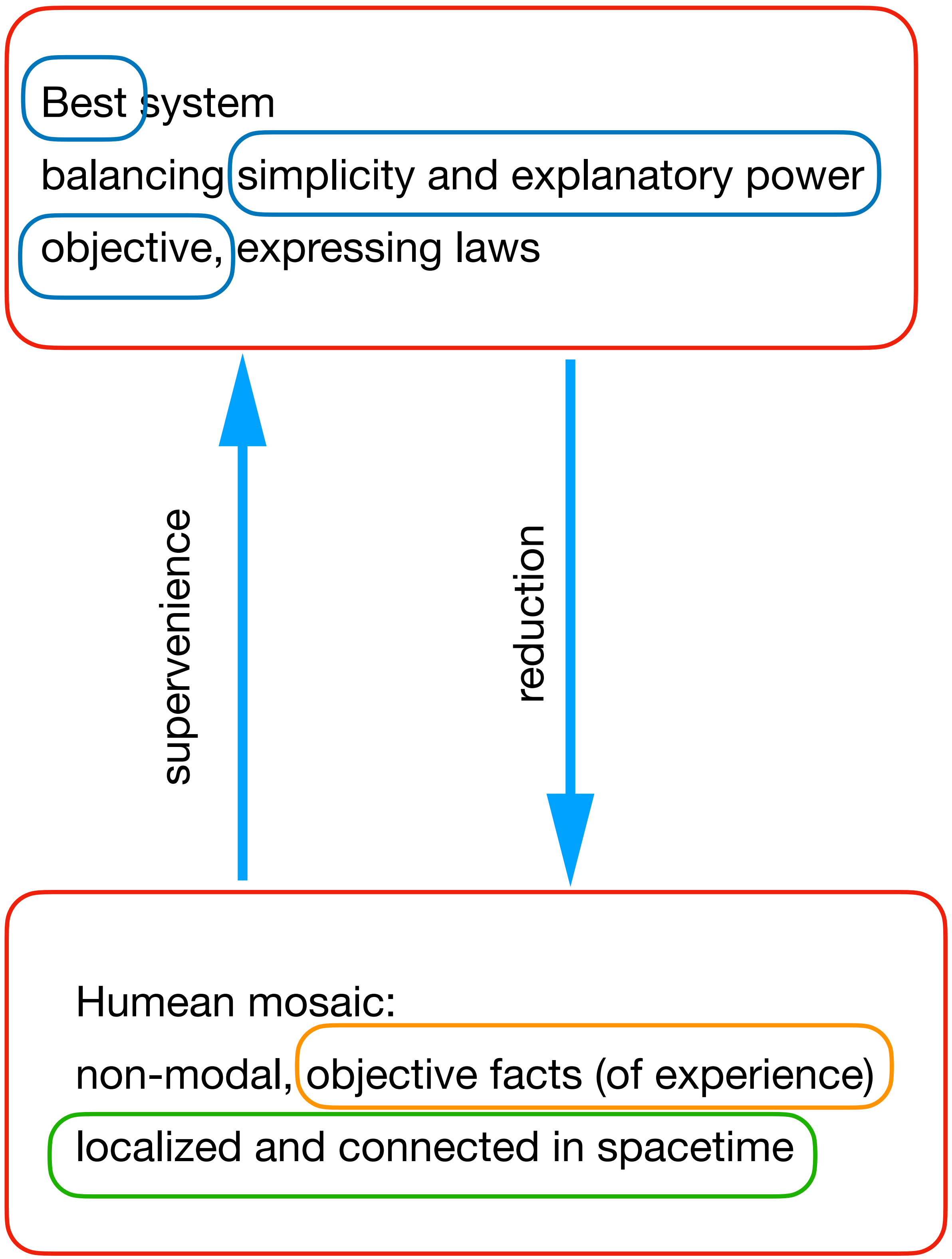
Humeanism - Lewis' best system



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law of nature = proposition that appears as an axiom or theorem of the 'best system'

best system = true, deductively closed theory which best balances simplicity in expression with strength in explanation of patterns of "facts" in the world (Humean mosaic)

"best" in metaphysical sense, not "currently best"

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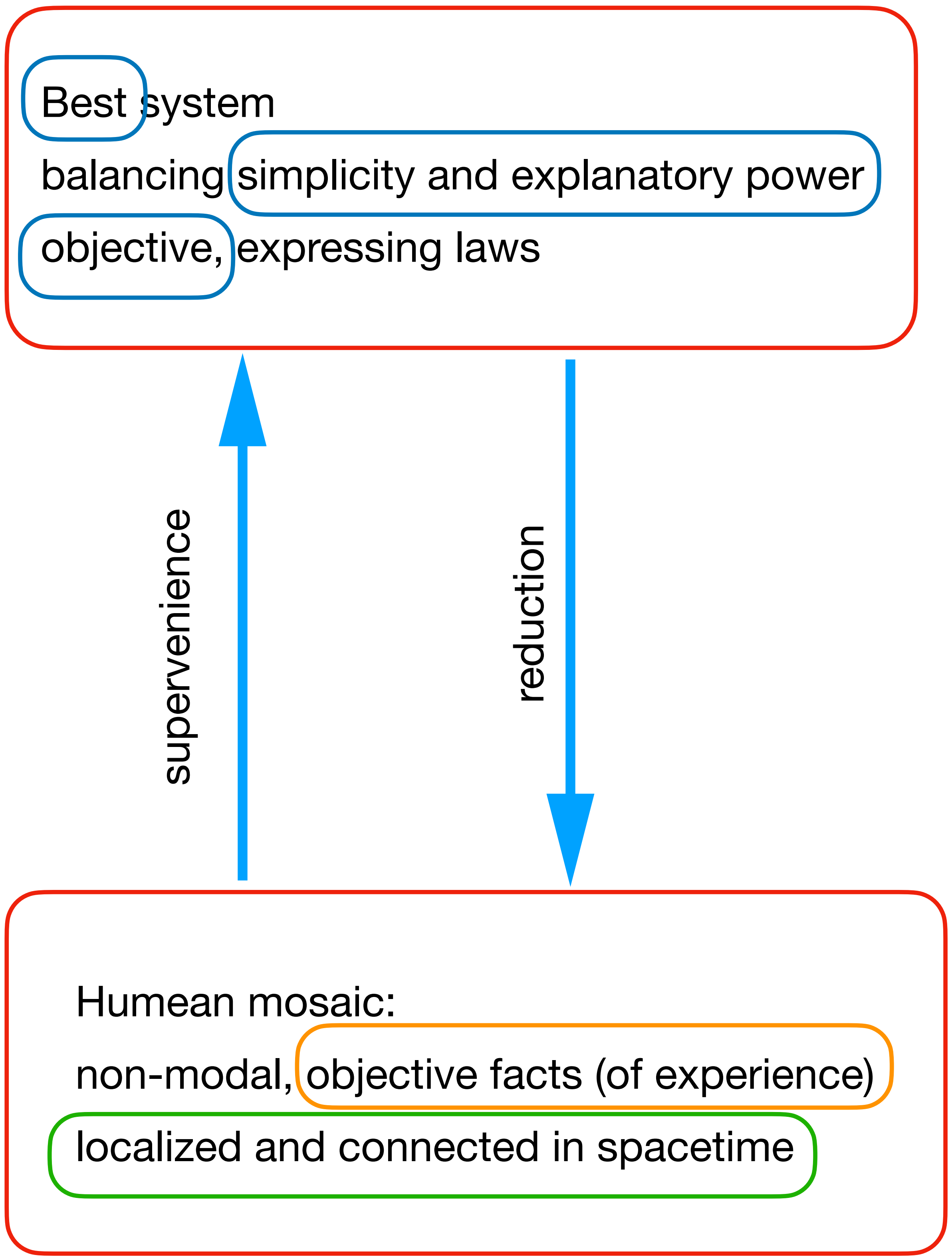

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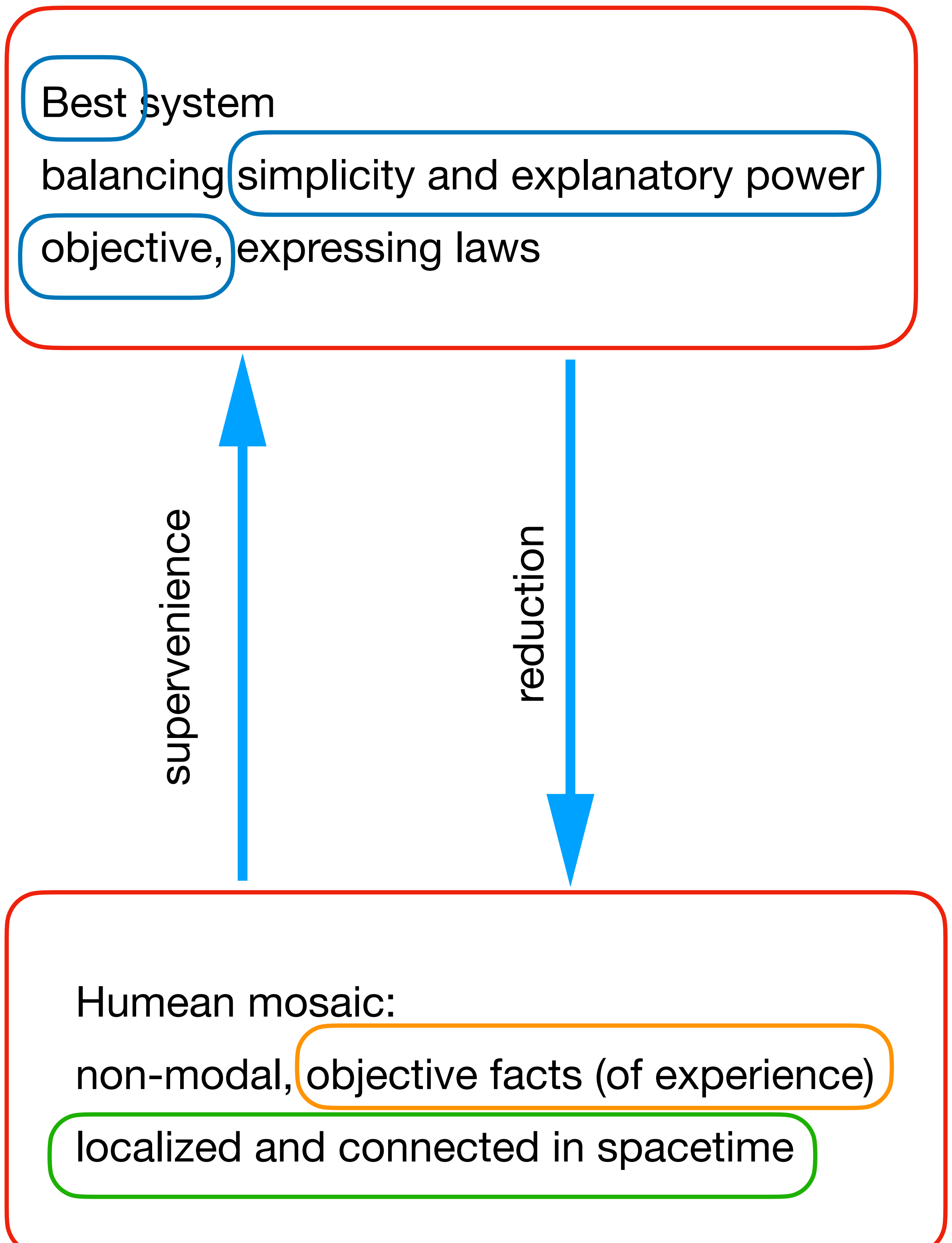

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quantum gravity challenges

Humeanism - Lewis' best system

Best system
balancing simplicity and explanatory power
objective, expressing laws

supervenience ↑ reduction ↓

Humean mosaic:
non-modal, objective facts (of experience)
localized and connected in spacetime

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- laws of nature are the product of intelligent agents; their role is irreducible and not negligible (outside ideaiizations)
- epistemic nature of laws and role of intelligent agents has concrete implication for (our understanding and formulation of) fundamental physics
    - resonances with (and inclinations towards) epistemic perspectives on QM
    - epistemic perspective on (dynamical) quantum causality, as foundation of quantum geometry

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→ the universe is (largely) what we think it is (or what we model it as)

Which quantum mechanics (or generalization thereof) without spacetime?

in all of the above, we have assumed and used standard Quantum Mechanics

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from QG perspective:

- some *suggestions*: only laws are "laws of rationality", rather than laws governing events in spacetime?

  only "laws of consistency across perspectives/participators"?

- one *call for action*: need to understand the "quantum principle" beyond spacetime

  - key issues: what are "participators"? what are (quantum) probabilities?

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resonances with:

Epistemic-pragmatist intepretations of QM

A. Barzegar, DO, 2210.13620 [quant-ph]

see also J. Pienaar, '21

- Bohr's views — Bohr, 1963
- Relational Quantum Mechanics — Rovelli, 1996, 2018
- Bub-Pitowsky Interpretation — Bub, Pitowski, 2010; Bub, 2017
- Müller's interpretation — Masanes, Müller, 2011; Müller, 2017
- Brukner-Zeilinger interpretation — Brukner, Zeilinger, 2000, 2002; Brukner, 2007
- Healey's pragmatism — Healey, 2012, 2017
- QBism — Fuchs, 2010, 2017

Which quantum mechanics (or generalization thereof) without spacetime?

resonances with:

Epistemic-pragmatist intepretations of QM: shared elements

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1. An "epistemic" (as opposed to ontic) view of quantum states

A quantum state is not in itself real. It represents knowledge, information or beliefs of the "observing system" in relation with the "observed system"

2. A metaphysics of participatory realism

The only subject matter of QM is the relation between two systems (the "observing" system and the "observed" system), the two poles of an interaction relation. We should move from an object-based ontology to a relation-based one. Reality is continuously shaped by the interaction between the two involved physical systems. This is a "participatory" and "relational" realism.

3. An epistemology of perspectival objectivity

If quantum states are a complete account of physical facts and they are relational, it follows that physical facts are necessarily perspectival. There is no perspective-independent fact. Facts (about physical systems) are irreducibly relative (to a perspective provided by other physical systems). The only possible form of objectivity is a weaker notion, which amounts to constraints on the possible perspectival accounts.

each of these ingredients deserves and requires much further philosophical analysis

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  - propensities ~ measures of dispositions — RQM
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- nature of physical laws is relevant for above issues — representational vs normative

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A. Barzegar, DO, 2210.13620 [quant-ph]

see also J. Pienaar, '21

- who (what kind of physical system) can play the role of "observer"?
  - any physical system — RQM
  - "complex (resourceful) enough" physical systems — Bub-Pitowski, Müller, Brukner-Zeilinger, Healey
  - full-fledged subjects — QBism
- what are "quantum probabilities"?
  - propensities ~ measures of dispositions — RQM
  - Bayesian probabilities
    - objective, evidence-based — Bub-Pitowski, Brukner-Zeilinger, Healey
    - subjective — QBism
- nature of physical laws is relevant for above issues — representational vs normative
- these issues have to be understood *without assuming/relying on spacetime*

Thank you for your attention!