What is spacetime?
and how does it come about?
the quest for quantum gravity

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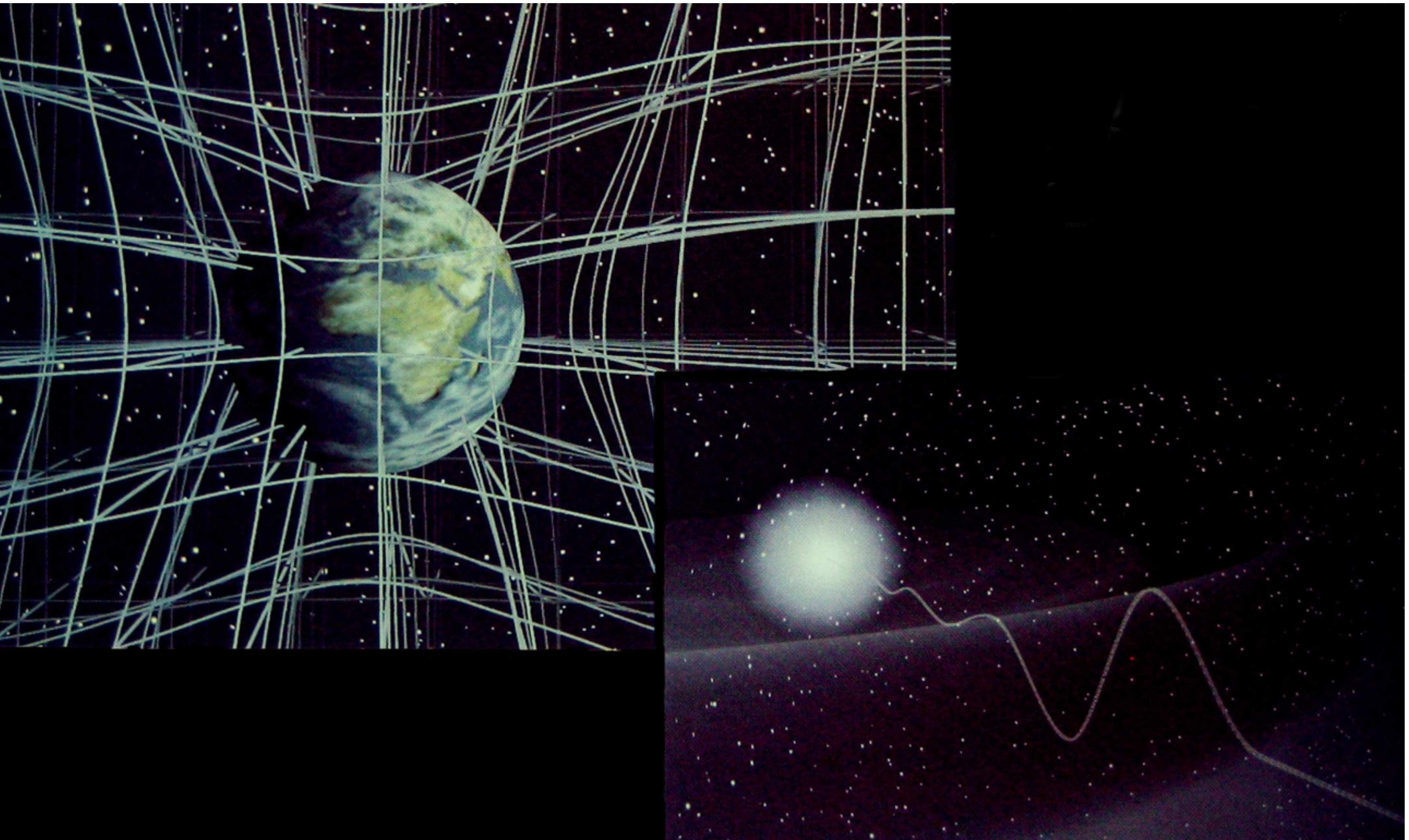
Quantum Gravity:
the problem

What we know about gravity and spacetime

- gravitational physics well described by General Relativity
  - basis for our description of astrophysics and cosmology
  - predicts amazing new phenomena (deflection of light, gravitational distortion of space and time measurements, gravitational waves, black holes, expansion of universe, …….)

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu} - \Lambda g_{\mu\nu}$$



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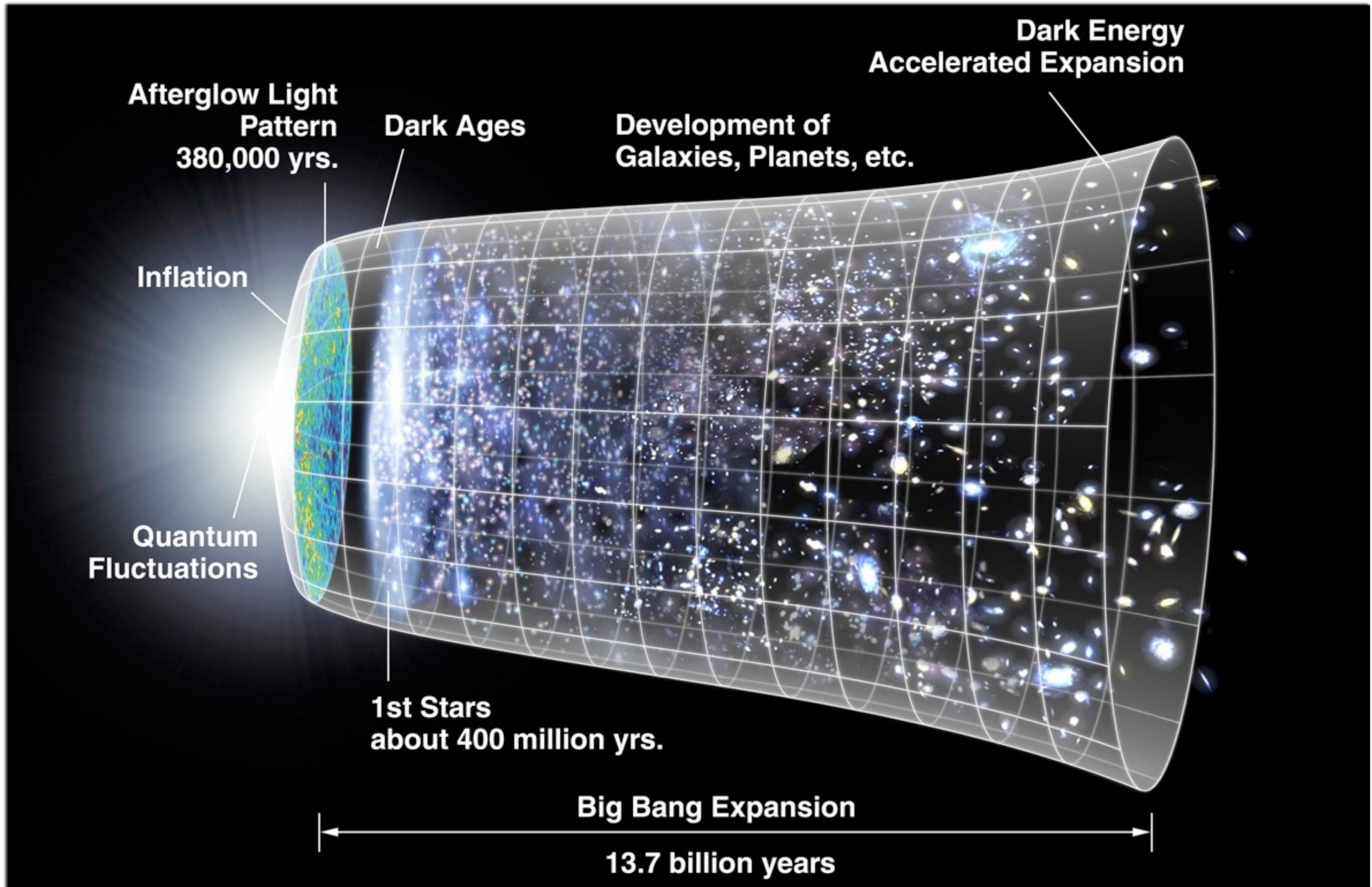

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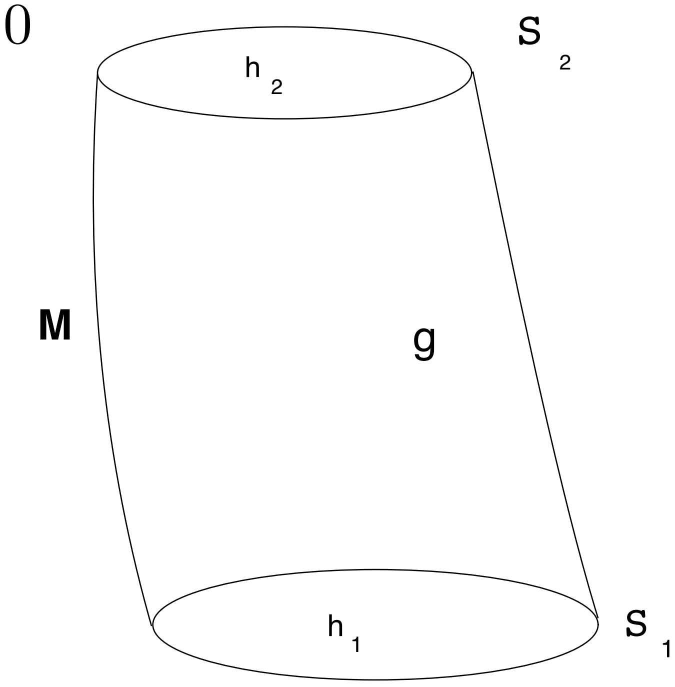
- what do we learn from GR?
  - gravitational interaction described (macroscopically) by geometry of spacetime
  - continuum, local picture of spacetime adequate
  - dynamics and (local) interaction with matter described by Einstein's equations: "matter tells spacetime how to curve, spacetime tells matter how to move"
  - spacetime itself is physical system
  - there is no fixed background over which things happen, if not as approximation
    - deeper understanding of gravity is deeper understanding of space and time

Space and Time in General Relativity

classical theory: $(\mathcal{M}\,, g)$ $\quad S_{\mathcal{M}}(g) \quad R_{\mu\nu}(g) - \frac{1}{2}R(g)g_{\mu\nu} + \Lambda\, g_{\mu\nu} = 0$



spacetime structures:

topological manifold

differentiable structure

("time" foliation vector, …)

continuum metric field

matter/gauge fields

GR key ingredients: only dynamical fields + diffeomorphism invariance

- no preferred time/space direction - infinity of equally valid local notions of time/space
- only dynamical and diffeo-invariant quantities are physical (correspond to predictions of theory)
- manifold points, paths on manifolds, values of fields at points or regions, are -not- physical per se
- they have to be made physical (given some operational meaning) by defining them via dynamical fields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Why we need to go beyond GR and QFT

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) and of their interactions 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

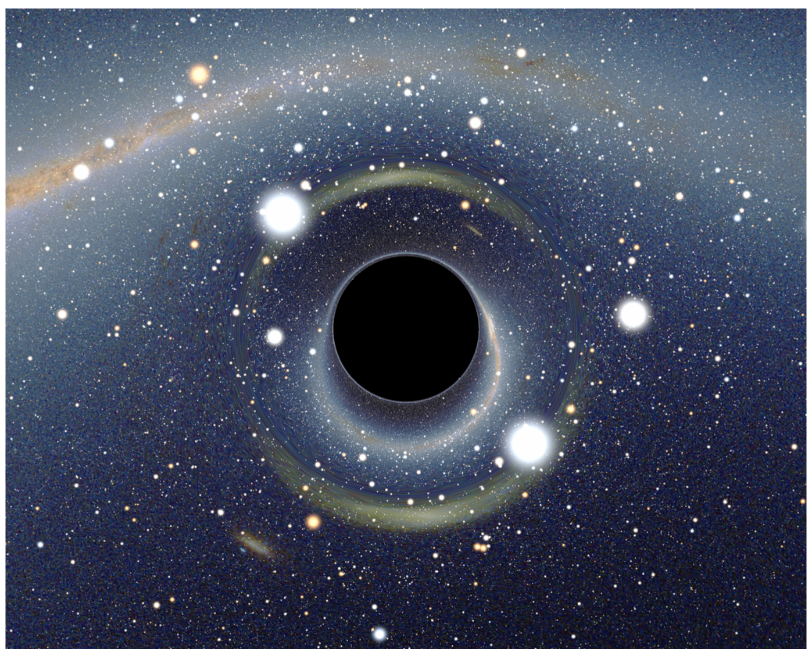
so, what are, really, space, time, geometry, and matter?

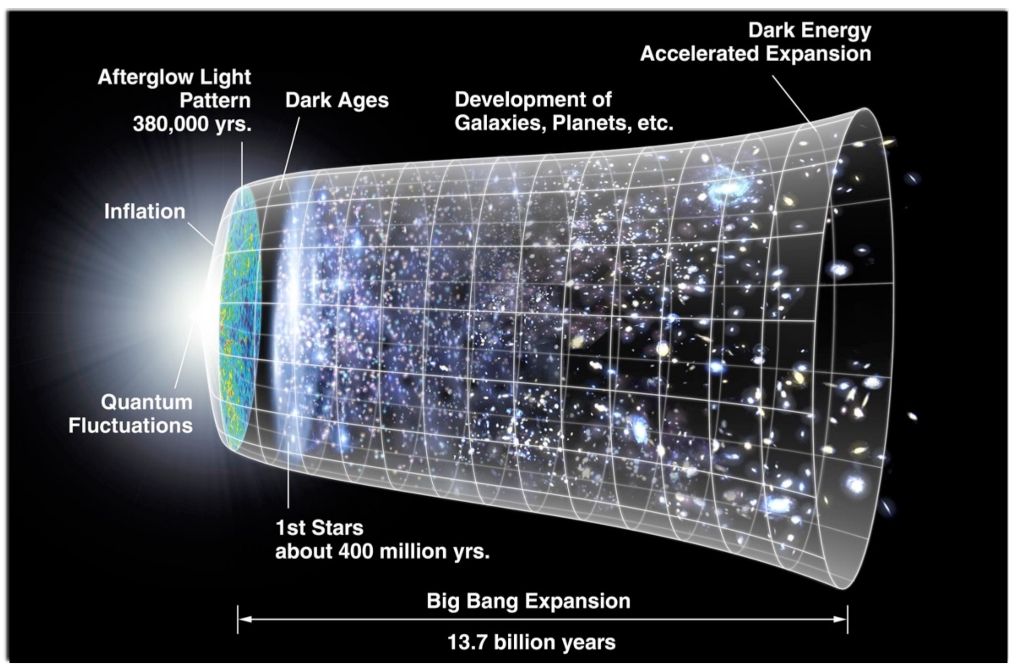
Why we need to go beyond GR and QFT

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





- 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?

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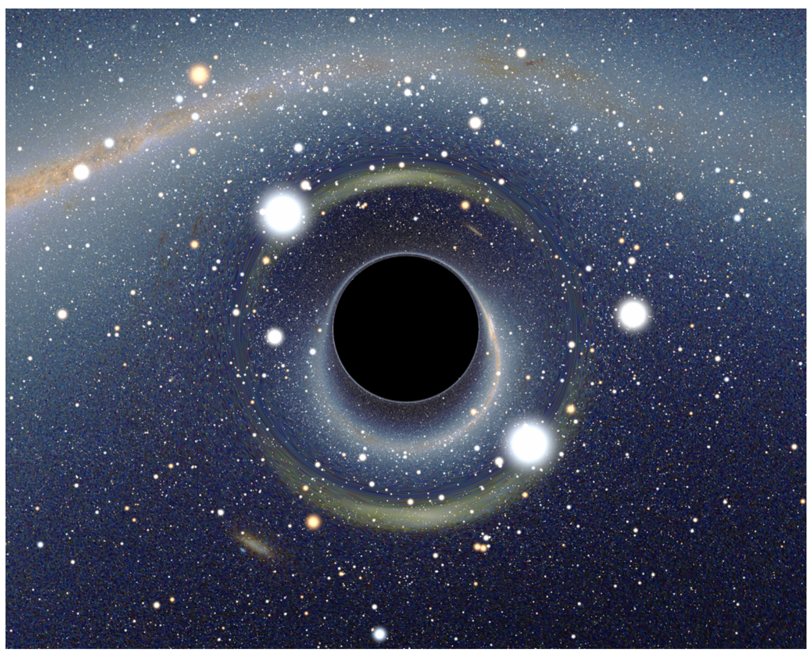
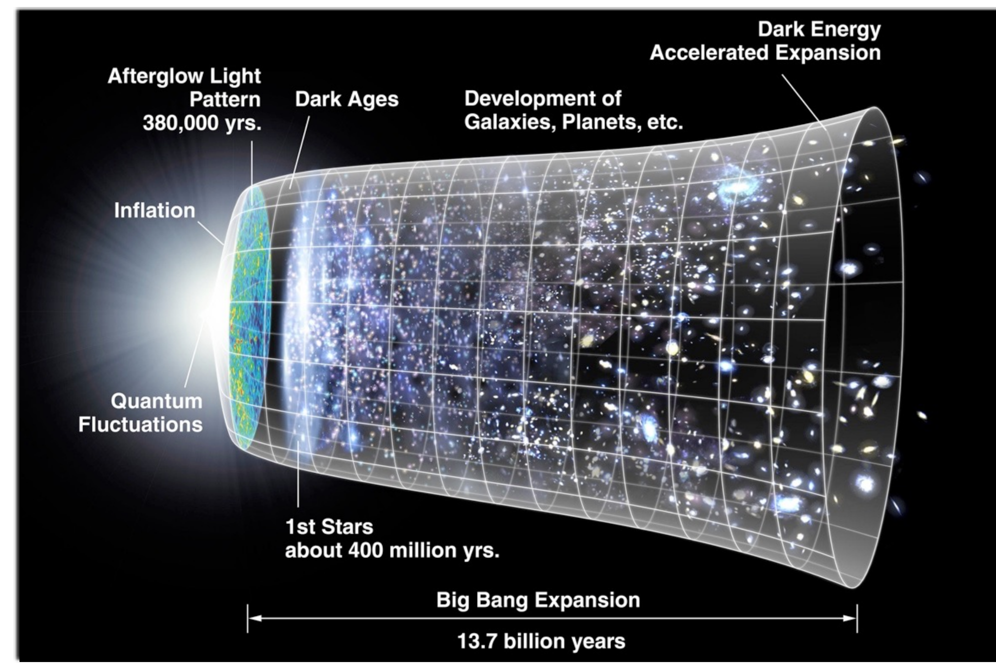




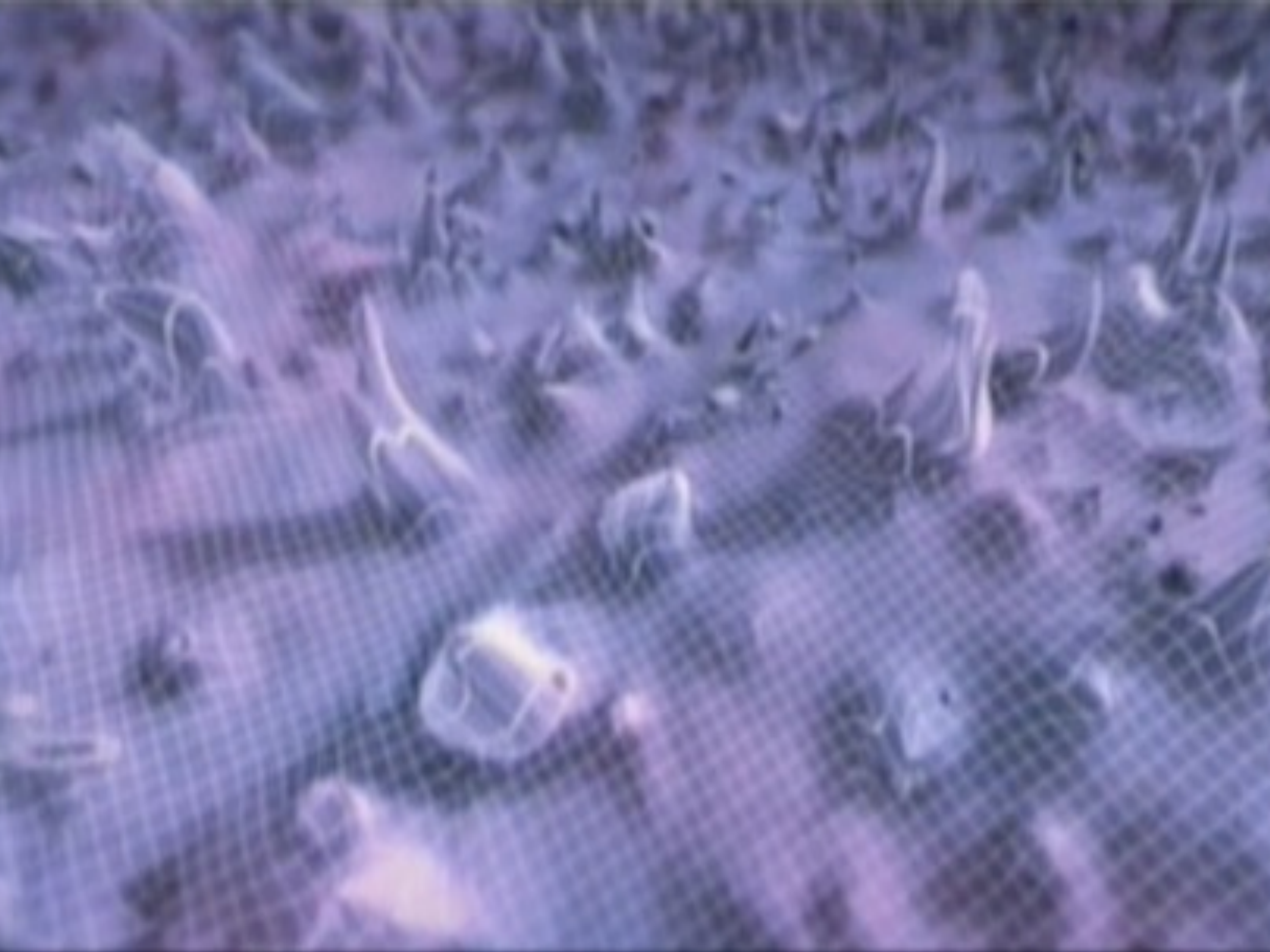
- divergences in QFT - what happens at high energies? how does spacetime react to such high energies?

- 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

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} \langle \Psi | \hat{T}_{\mu\nu} | \Psi \rangle$$

not a consistent theory



Why we need to go beyond GR and QFT

hints of disappearance of spacetime itself, more radical departure from GR and QFT

- challenges to "localization" in semi-classical GR

  minimal length scenarios

- spacetime singularities in GR

  breakdown of continuum itself?

- black hole thermodynamics

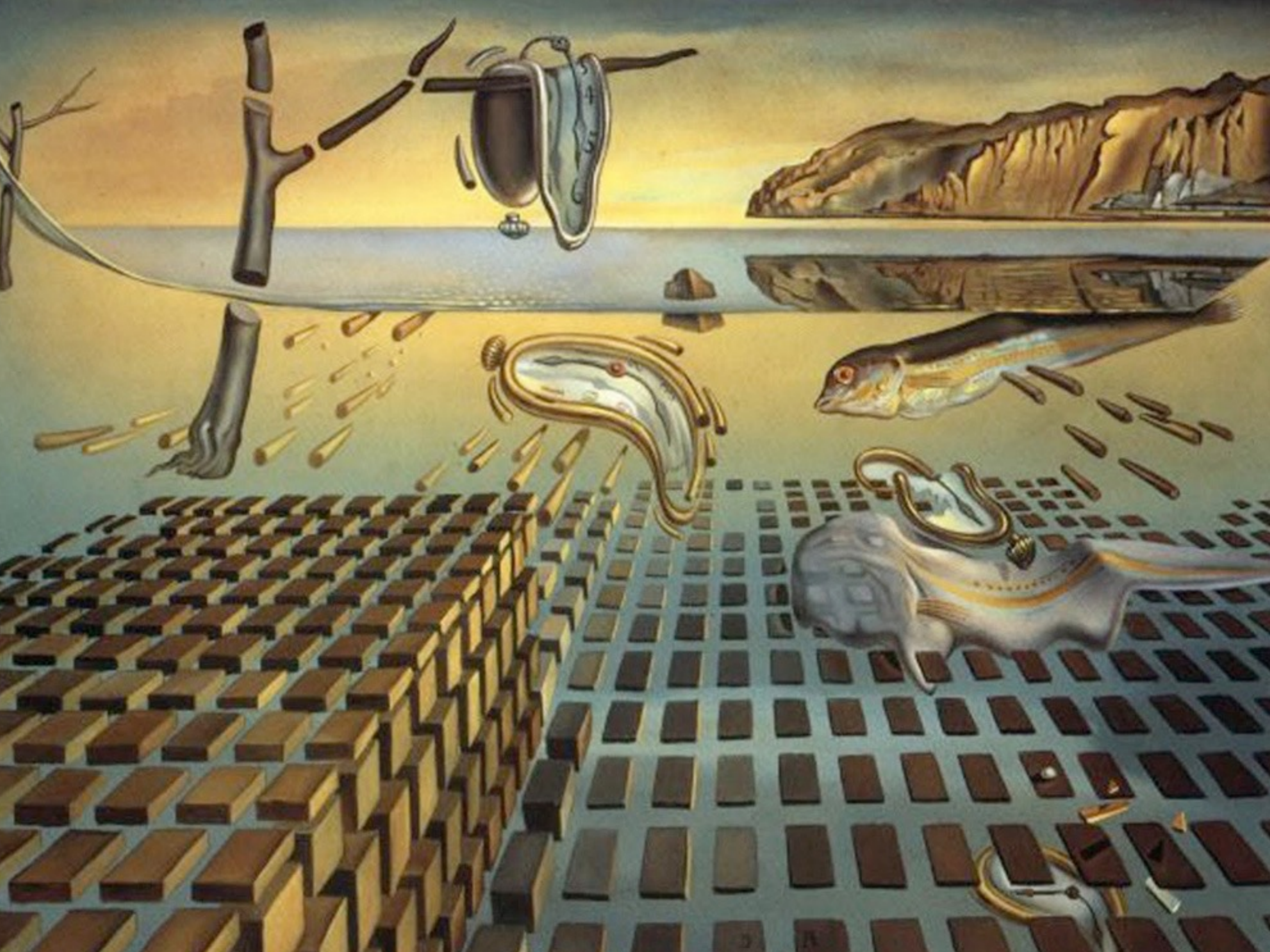
  black holes satisfy thermodynamic relations

  if spacetime itself has (Boltzmann) entropy, it has microstructure
  if entropy is finite, this implies discreteness

- Einstein's equations as equation of state (Jacobson et al)

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

fundamental discreteness of spacetime?
is spacetime itself "emergent" from non-spatiotemporal, non-geometric,
quantum building blocks ("atoms of space")?



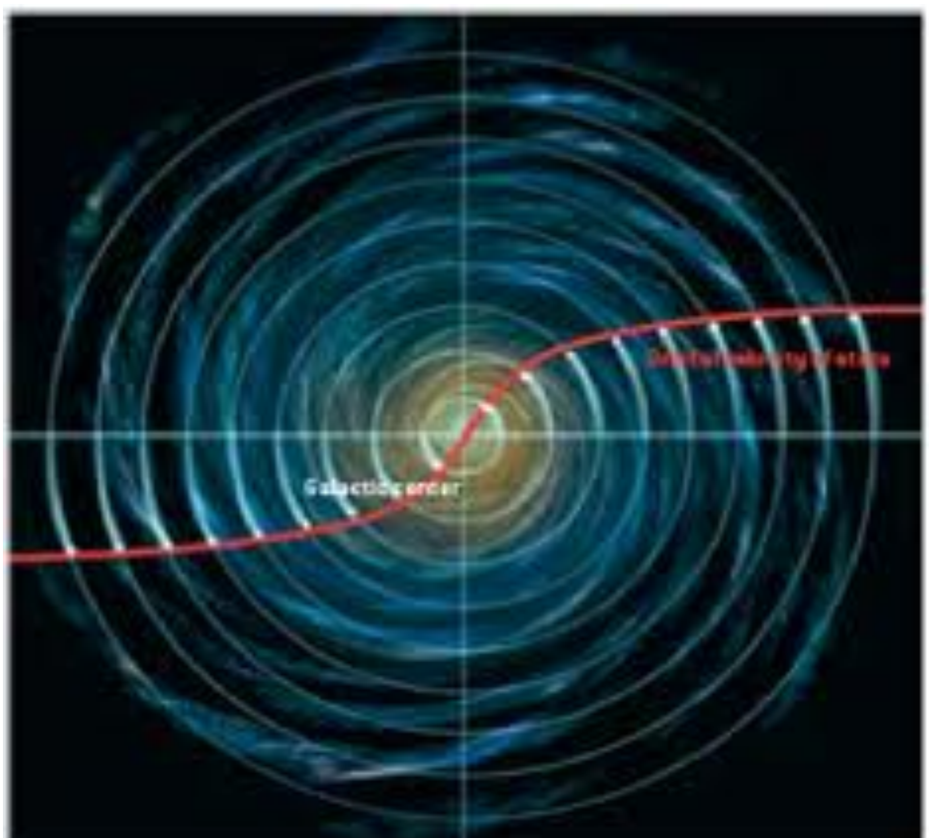
Why we need to go beyond GR and QFT

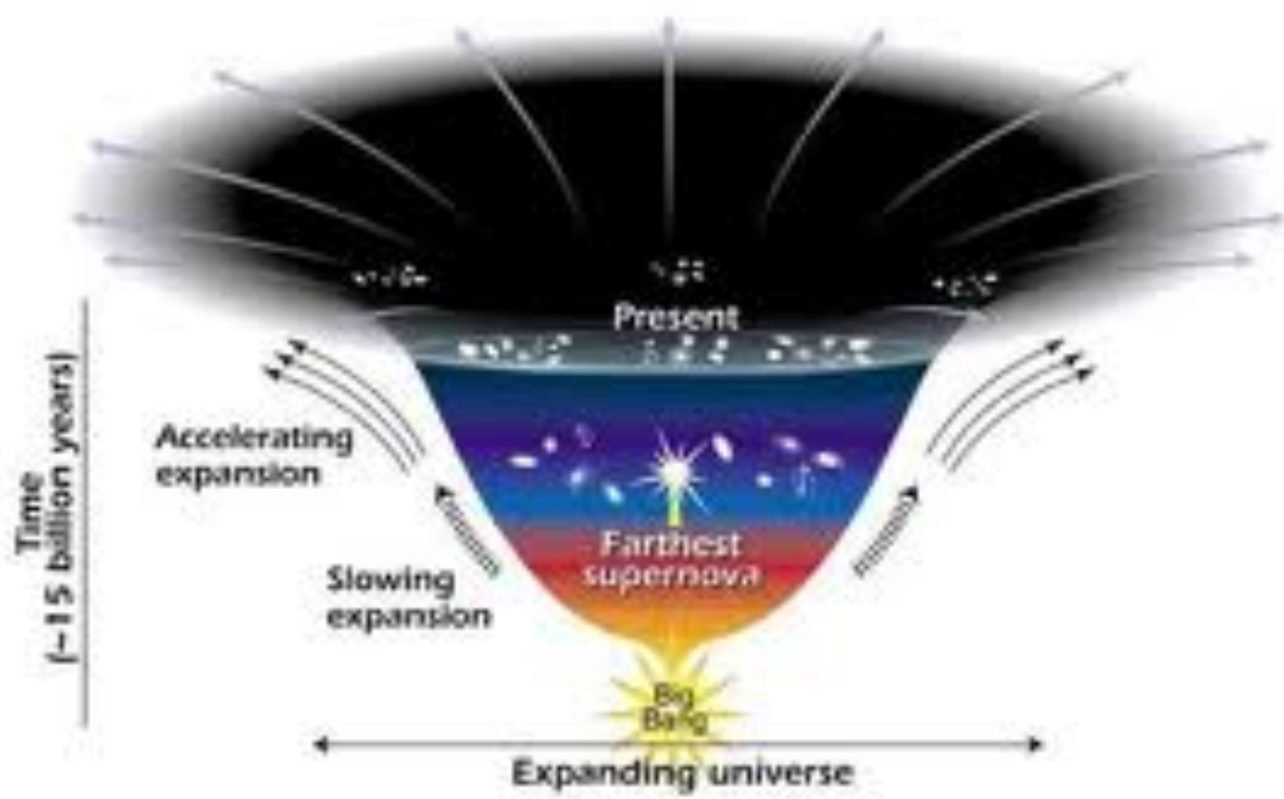
if spacetime (with its continuum structures, metric, matter fields, topology) is emergent,

even large scale features of gravitational dynamics can (and maybe should) have their origin in more fundamental ("atomic") theory

cannot trust most notions on which effective quantum field theory is based (locality, separation of scales, etc)

e.g. : dark matter (galactic dynamics), dark energy (accelerated cosmological expansion) - either 95% of the universe is not known, or we do not understand gravity at large scales

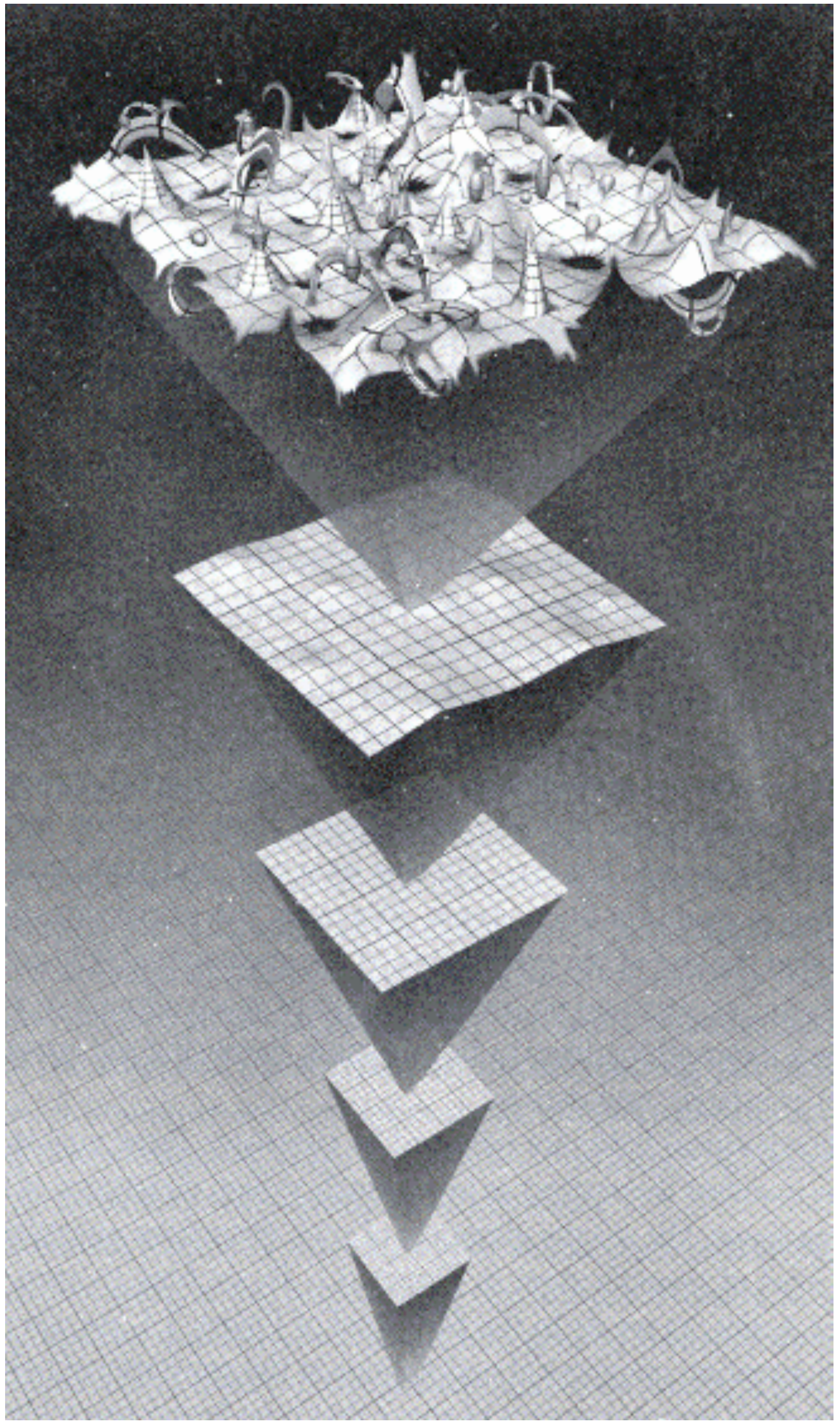




e.g. cosmological constant as possible large scale manifestation of microscopic (quantum gravity) physics

What has to change (in going from GR to QG)

- quantum fluctuations (superpositions) of spacetime structures
  - geometry (areas, distances, volumes, curvature, etc)
  - causality (causal relations)
  - topology?
  - dimensionality?
- breakdown of continuum description of spacetime?
  - fundamental discreteness? of space only? of time as well?
  - entirely new degrees of freedom - “atoms of space”? which ones?
  - but then, how does usual spacetime “emerge”?
- new QG scale: Planck scale



What could be the relevant scale for QG effects?

based on current theories, i.e. GR and QFT: Planck scale

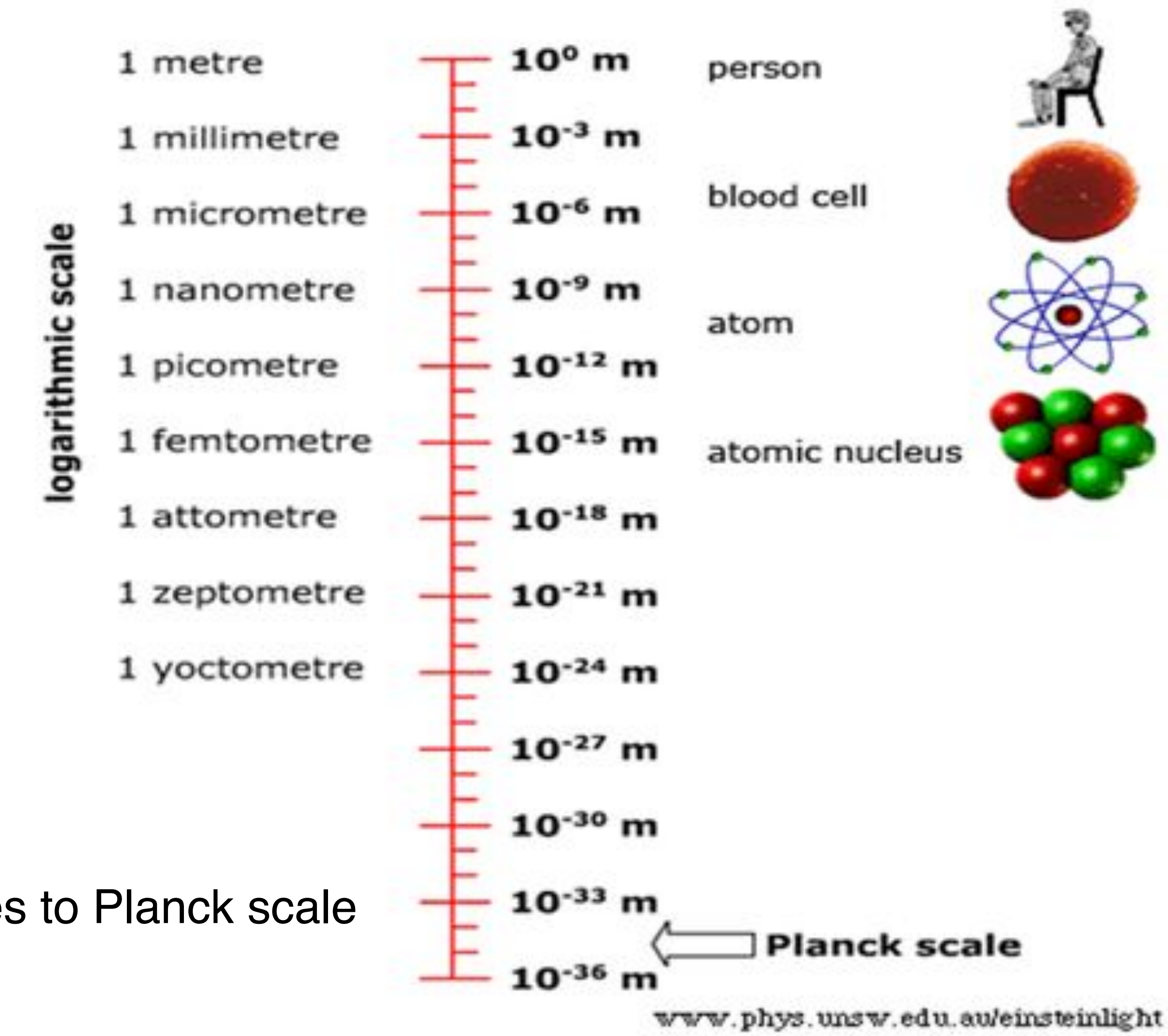
~ where both GR and QFT are relevant

$$l = \sqrt{\frac{Gh}{c^3}} = 3.99 \times 10^{-33}\ cm = 3.99 \times 10^{-35}\ m,$$

$$m = \sqrt{\frac{ch}{G}} = 5.37 \times 10^{-5}\ g = 5.37 \times 10^{-8}\ kg,$$

$$t = \sqrt{\frac{Gh}{c^5}} = 1.33 \times 10^{-43}\ \text{sec},$$

$$T = \frac{1}{k}\sqrt{\frac{c^5 h}{G}} = 3.60 \times 10^{32}\ \text{deg}\ K.$$



in principle, Quantum Gravity from cosmological scales to Planck scale

cautionary remark: this is on the basis of current physics, tested only up to very different scales (compared to Planck scale) and based on concepts that may not be valid beyond such scales

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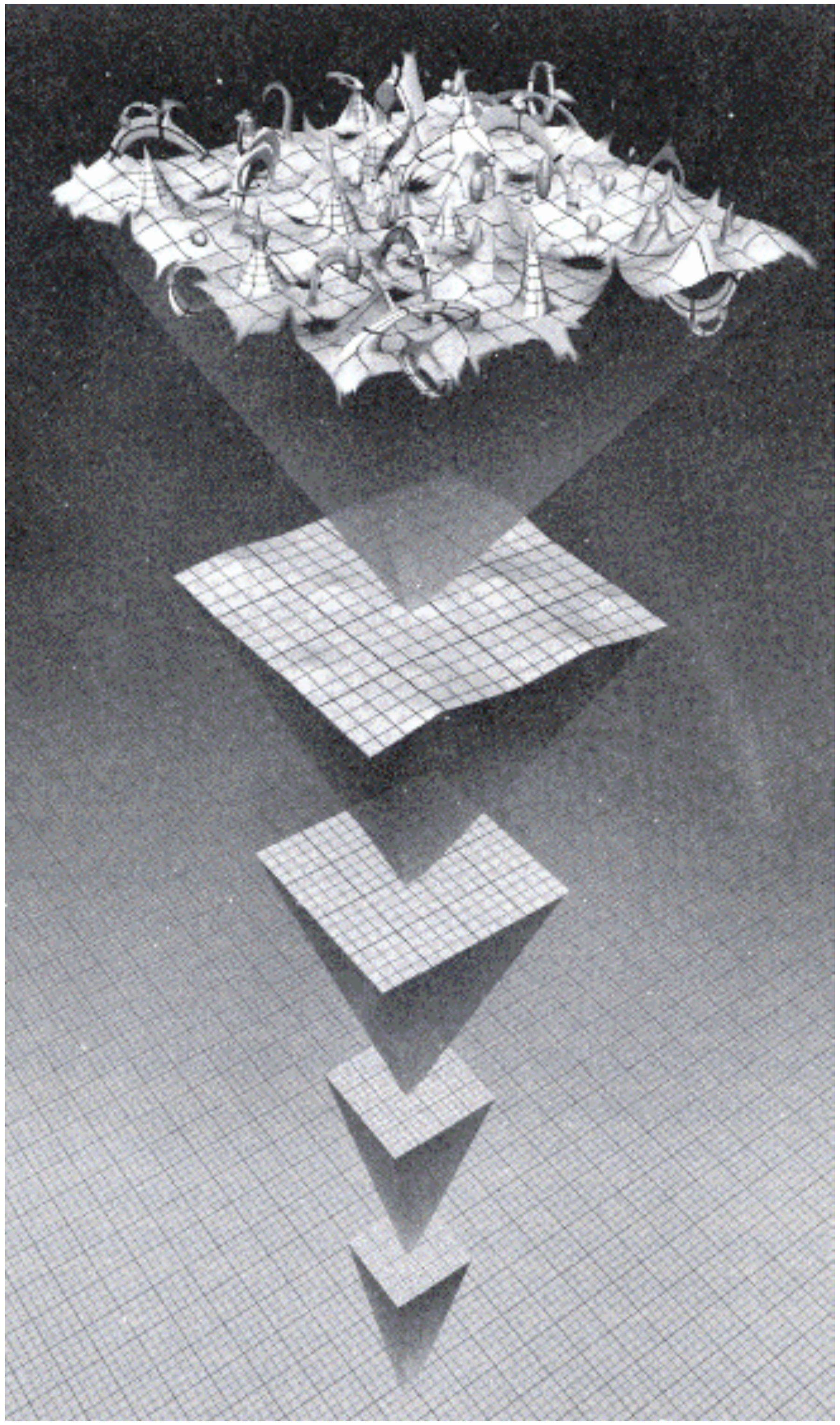
no spacetime or geometry?

how can we even talk of “scales”?

total failure of effective field theory intuition?



Quantum Gravity and the nature of spacetime

Quantum Gravity is not about “quantizing GR”, but about understanding the “microstructure of spacetime”

quantum gravity = microscopic theory of pre-geometric quantum degrees of freedom
(“quantum (field) theory of atoms of space”)

the goals are:

- identify the fundamental (quantum) degrees of freedom of spacetime
  —— the “atoms of space (or spacetime)” and their quantum dynamics
- show that an approximately continuum, classical spacetime emerges
- show that GR is good effective description of emergent spacetime dynamics

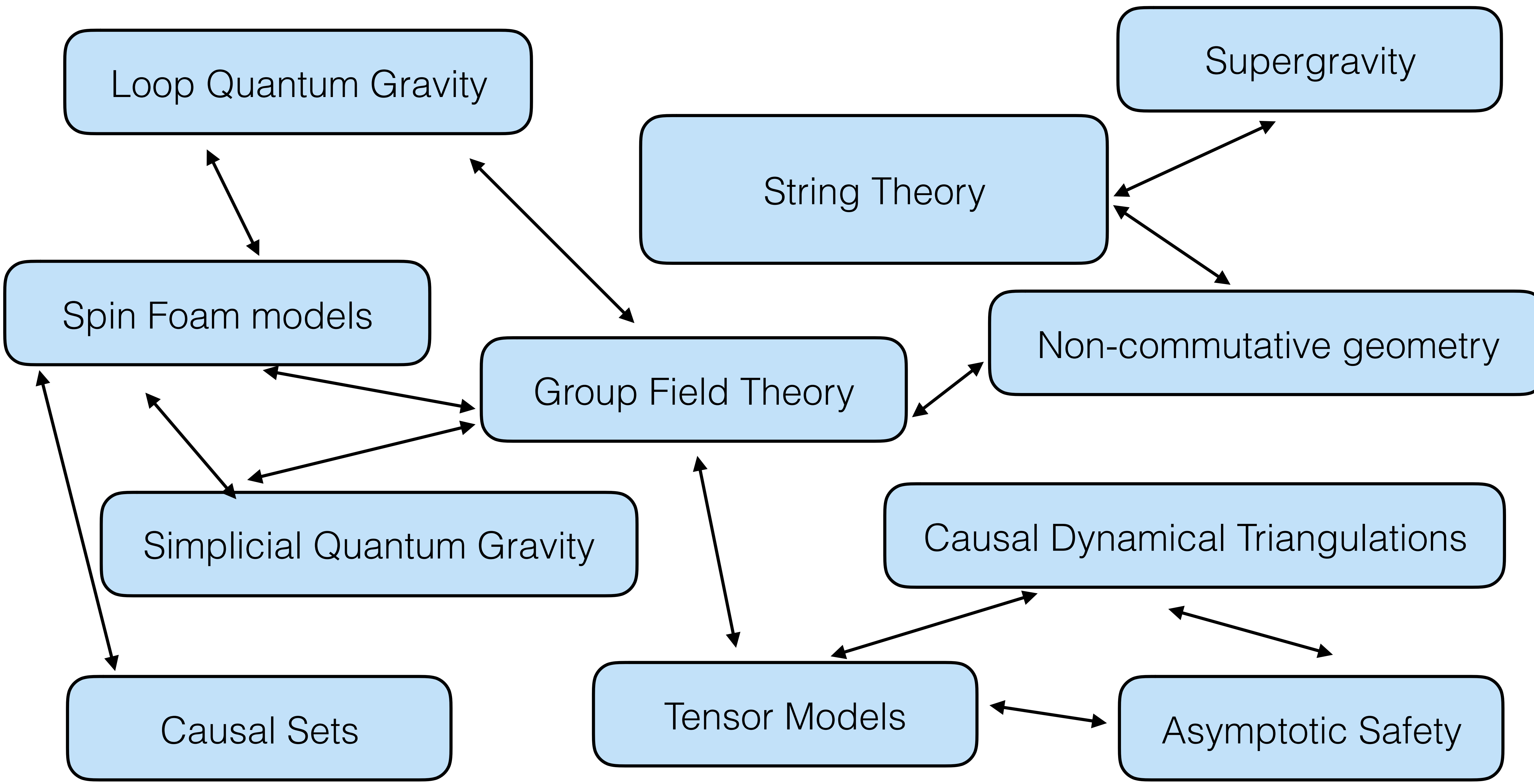
gravitational field result of collective dynamics

→ spacetime and geometry are emergent entities, obtained after coarse graining of fundamental, non-spatiotemporal dofs

candidate “atoms of quantum space” ——-> how to recover continuum spacetime (and GR)?

Quantum Gravity:
variety of approaches

Quantum Gravity: contemporary approaches



String theory (and related)

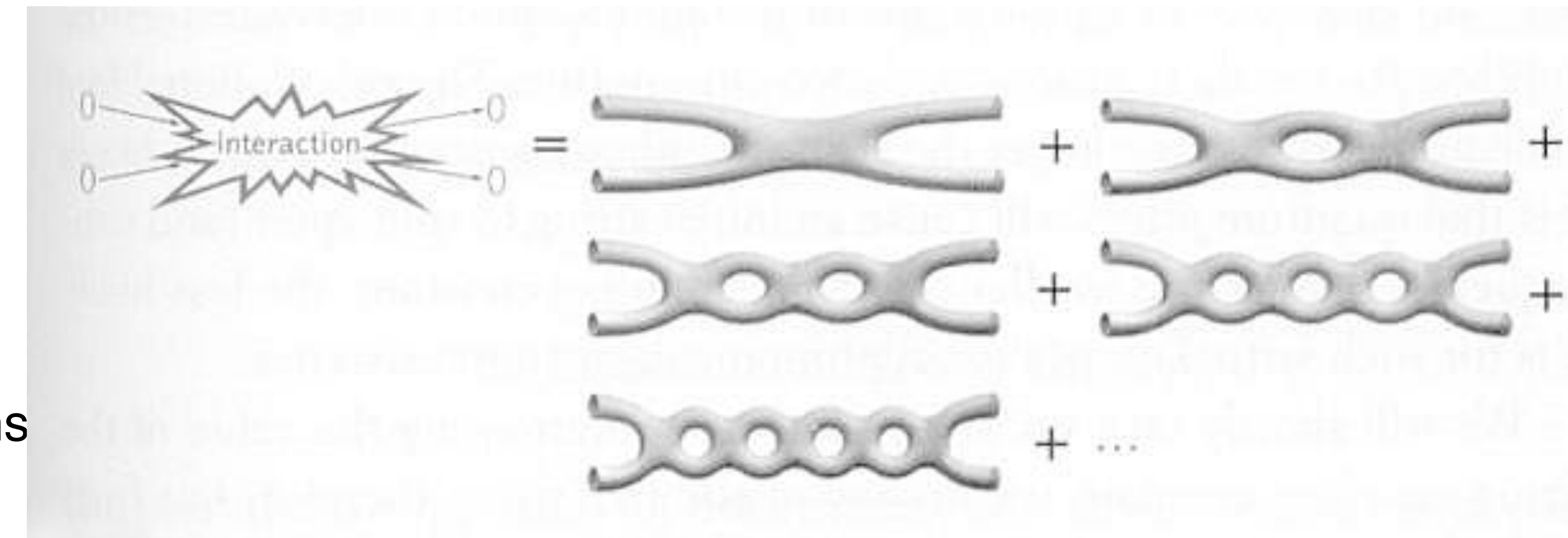
(…… , a lot of people, …..)

starting idea: quantum theory of strings, interacting and propagating on given spacetime background

string excitations: particles of any spin/mass; incl. graviton = quantum of gravitational field

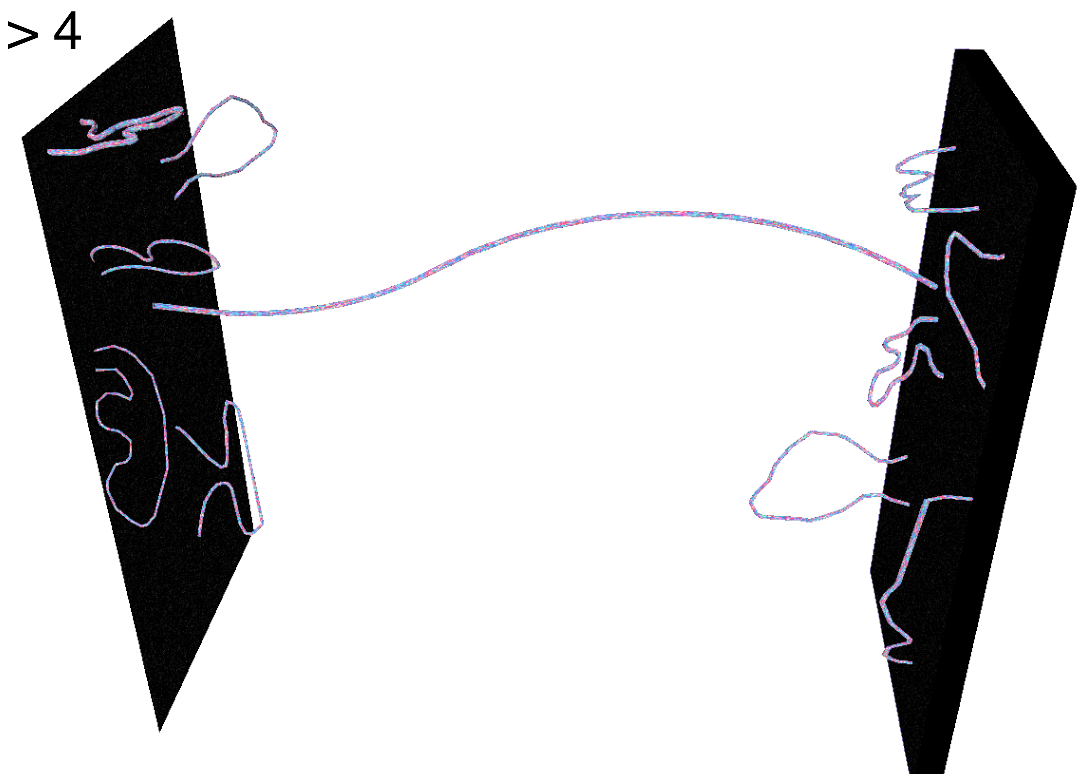
consistent (around flat space) and finite perturbation theory in 10d

background spacetime satisfies GR equations



many different (consistent) versions (different matter content, different symmetries) - all require supersymmetry and spacetime dimension > 4

central result: spacetime as seen by strings, as opposed to point particles/fields, has very different topology and geometry; e.g. distances smaller than minimal string length cannot be probed

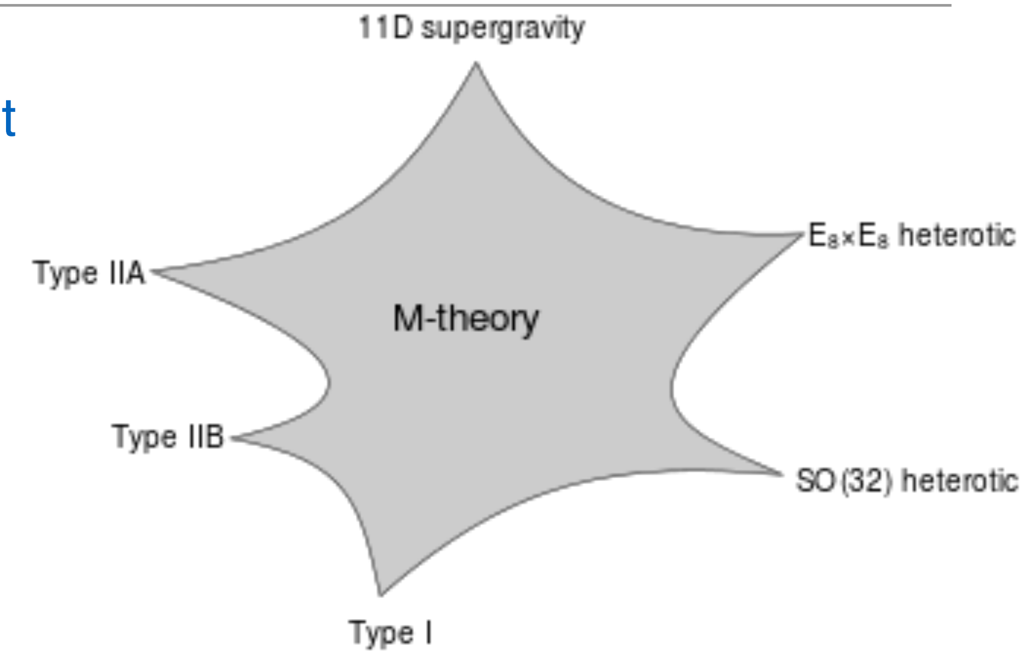


many non-perturbative aspects; extended (d>1) configurations (branes) as fundamental as strings, and interacting with them (Polchinski, …., 1994 -)

String theory (and related)

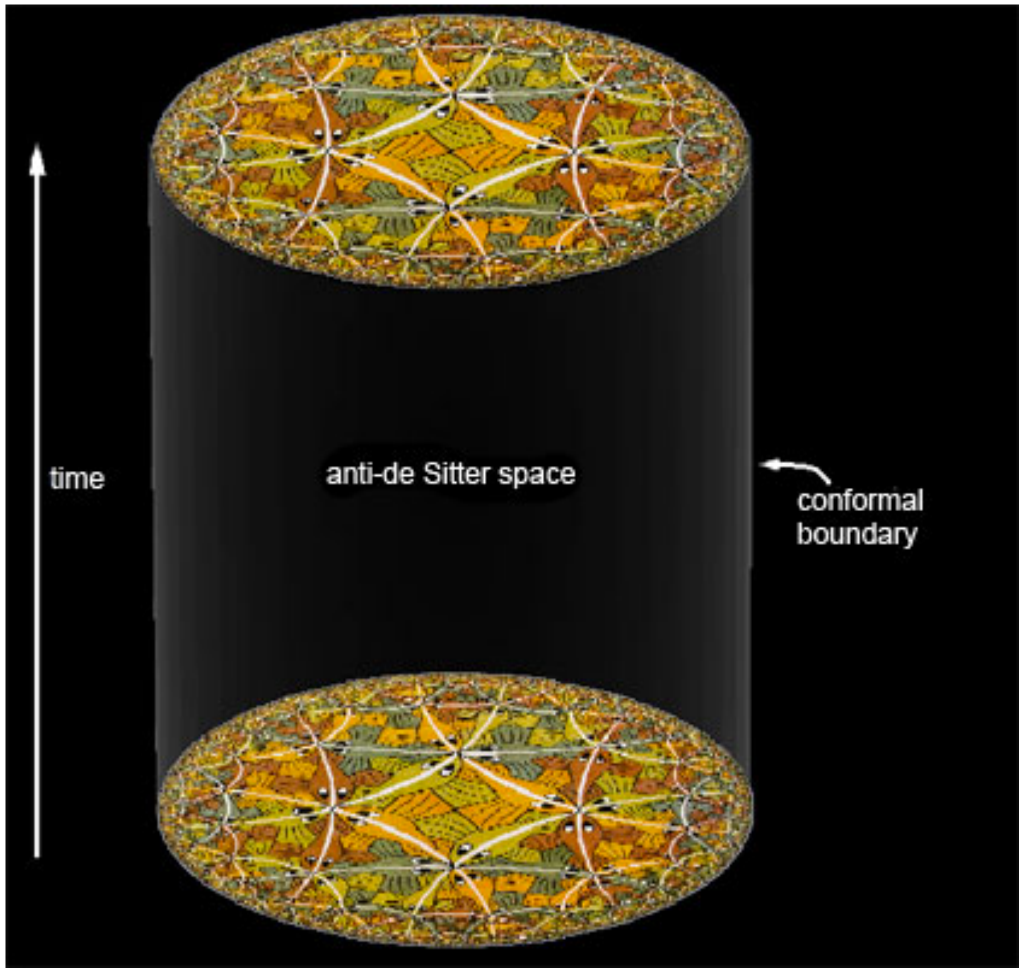
(…… , a lot of people, …..)

dualities between various string theories and supergravity: different aspects of same underlying fundamental theory (M-theory)?



dualities show that spacetime topology and dimension are themselves dynamical

AdS/CFT correspondence: a (gauge) QFT with conformal invariance on 4d flat space could fully encode the physics of a gravitational theory in 5d (with AdS boundary); viceversa, semiclassical GR (with extra conditions) could describe the physics of a peculiar many-body quantum system in different dimension



is the world holographic? are gravity and gauge theories equivalent? many results and new directions

large number of mathematical results and radical generalisation of quantum field theory

QG as (Effective) QFT - Asymptotic Safety Scenario

Quantum gravity is perturbatively non-renormalizable, as a QFT for the metric field (e.g. around Minkowski space)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

can still be used as effective field theory (incorporating quantum (loop) corrections) with fixed cutoff

$$S_{grav} = \int d^4x \sqrt{g} \left[\Lambda + \frac{2}{\kappa^2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \ldots + \mathscr{L}_{matter} \right]$$

J. Donoghue, C. Burgess, …..

and it is predictive (eg graviton scattering and corrections to Newtonian potential)

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Can it make sense non-perturbatively? **Asymptotic safety scenario**

S. Weinberg, M. Reuter, C. Wetterich, R. Percacci, D. Benedetti, A. Eichhorn, ….

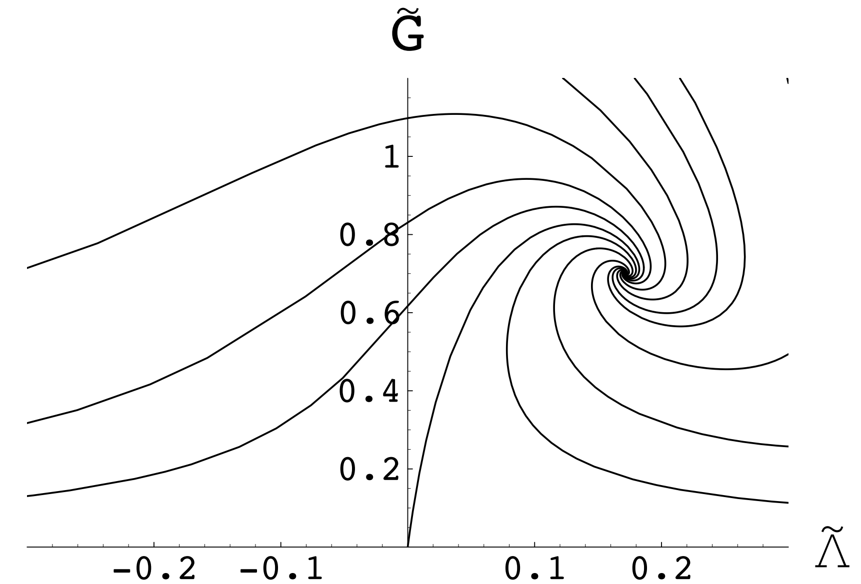
Effective action
(~ covariant path integral)

$$\Gamma_k(g_{\mu\nu}; g_i^{(n)}) = \sum_{n=0}^{\infty} \sum_i g_i^{(n)}(k) \mathcal{O}_i^{(n)}(g_{\mu\nu})$$

as solution to non-perturbative RG equations (e.g. Wetterich eqn)

$$\partial_t \Gamma_k = \frac{1}{2} \mathrm{STr} \left(\frac{\delta^2 \Gamma_k}{\delta\phi_A \delta\phi_B} + R_k^{AB} \right)^{-1} \partial_t R_k^{BA}$$

look for non-Gaussian UV fixed points



necessarily studied in various truncations (+ matter fields etc)

eg Einstein-Hilbert truncation

$$\Gamma_k^{(n\leq 2)} = \int d^dx \sqrt{g} \left[2Z_g\Lambda - Z_g R + \frac{1}{2\lambda} C^2 + \frac{1}{\xi} R^2 \right]$$

QG as canonical and/or covariant quantization of GR

Canonical quantization of GR:

3+1 splitting of manifold and fields; canonical phase space of 3-metric and extrinsic curvature

$$[\hat{h}_{ab}(x), \hat{p}^{cd}(y)] = \mathrm{i}\hbar\delta^c_{(a}\delta^d_{b)}\delta(x,y)$$

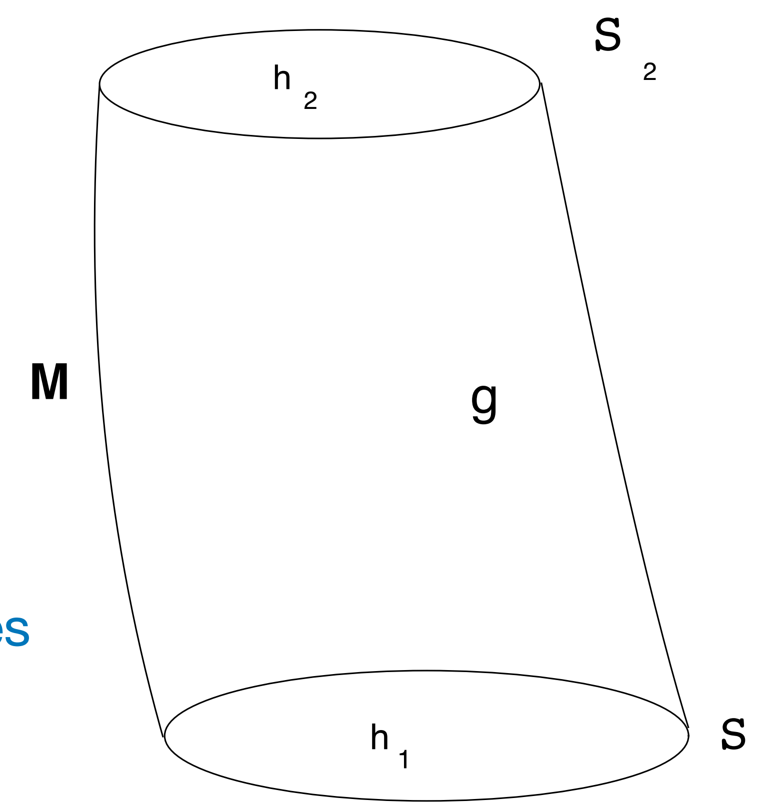
wavefunctions depend in 3-metric or extrinsic curvature

symmetries and dynamics fully encoded in diffeomorphism and Hamiltonian constraints

$$\hat{\mathcal{H}}_\perp\Psi \;:=\; \left(-16\pi G\hbar^2 G_{abcd}\frac{\delta^2}{\delta h_{ab}\delta h_{cd}} - \frac{\sqrt{h}}{16\pi G}\left({}^{(3)}R - 2\Lambda\right)\right)\Psi = 0,$$

$$\hat{\mathcal{H}}_a\Psi \;:=\; -2D_b h_{ac}\frac{\hbar}{\mathrm{i}}\frac{\delta\Psi}{\delta h_{bc}} = 0.$$

no time/space dependence



Covariant (path integral) quantization of GR:

$$Z[g] = \int \mathcal{D}g_{\mu\nu}(x)\; \mathrm{e}^{\mathrm{i}S[g_{\mu\nu}(x)]}$$

and transition amplitudes

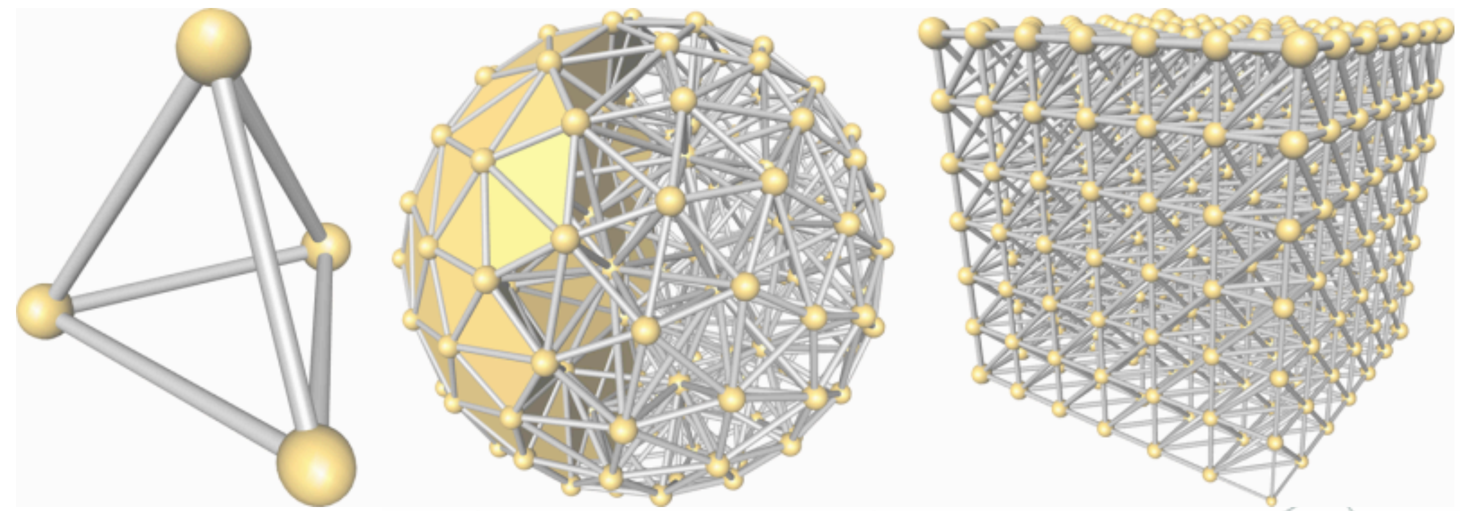
formidable mathematical (and conceptual) difficulties

functional aspects

diffeomorphism symmetry

………..

Lattice Quantum Gravity

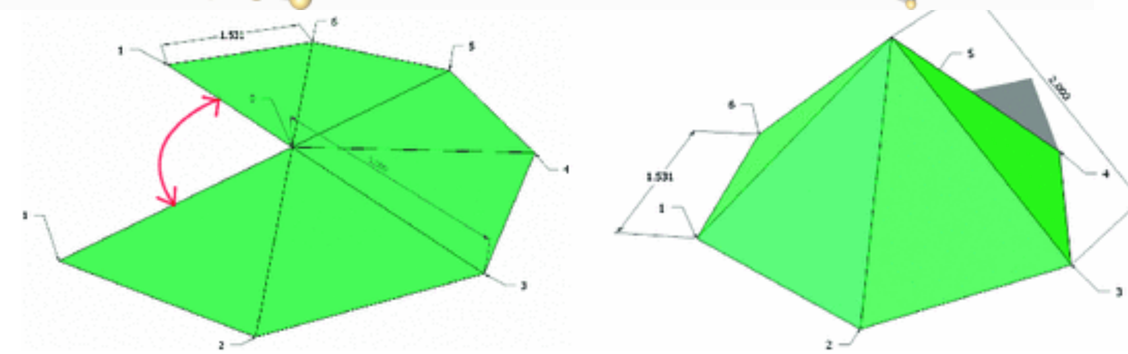


Basic idea: covariant quantisation of gravity as sum over “discrete geometries”

Continuum spacetime manifold replaced by simplicial lattice; metric data encoded in edge lengths

Gravitational action is discretised version of Einstein-Hilbert action (Regge action)

$$S_R = \frac{1}{8\pi} \sum_t A_t \varepsilon_t$$



Quantum Regge calculus

T. Regge, R. Williams, H. Hamber, B. Dittrich, B. Bahr, ….

Path integral of discrete geometries:

fixed simplicial lattice, sum over edge length variables

continuum limit via lattice refinement

$$Z \;=\; lim_{\Delta\to\infty} \int d\mu(\{L_e\})\, e^{-\,S_R^{\Delta}(\{L_e\})}$$

(Causal) Dynamical Triangulations

J. Ambjorn, J. Jurkiewicz, R. Loll, D. Benedetti, A. Goerlich, T. Budd, …

Path integral of discrete geometries:

sum over all possible (causal) simplicial lattices (fixed topology), fixed edge lengths

continuum limit via sum over finer and finer lattices

$$Z \;=\; lim_{a\to 0} \sum_{\Delta} \mu(a,\Delta)\, e^{-\,S_R^{\Delta}(\{L_e = a\})}$$

Loop Quantum Gravity (and spin foam models)

A. Ashtekar, C. Rovelli, L. Smolin, T. Thiemann, J. Lewandowski, J. Pullin, H. Sahlmann, B. Dittrich, ……

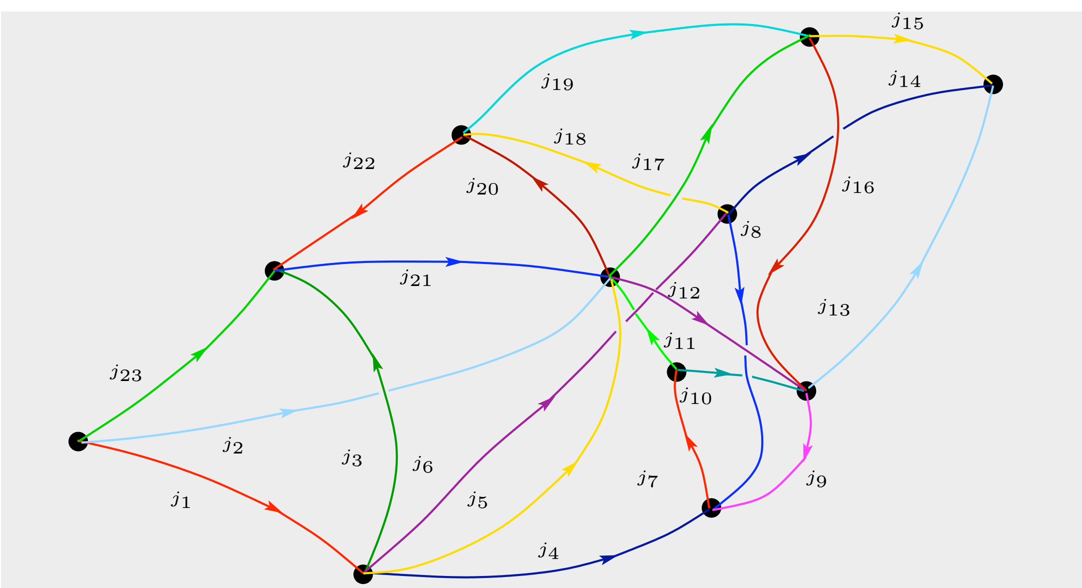
Canonical quantization of GR as gauge theory (connection variables): $\left(A_a^i \quad , \quad E_i^b = \frac{1}{\gamma}\sqrt{e}\, e_i^b\right)$

quantum states of "space" are graphs labeled by algebraic (group-theoretic) data: spin networks

kinematical Hilbert space of quantum states: $\mathcal{H} = \lim_{\gamma} \frac{\bigcup_\gamma \mathcal{H}_\gamma}{\approx} = L^2\left(\bar{\mathcal{A}}\right)$

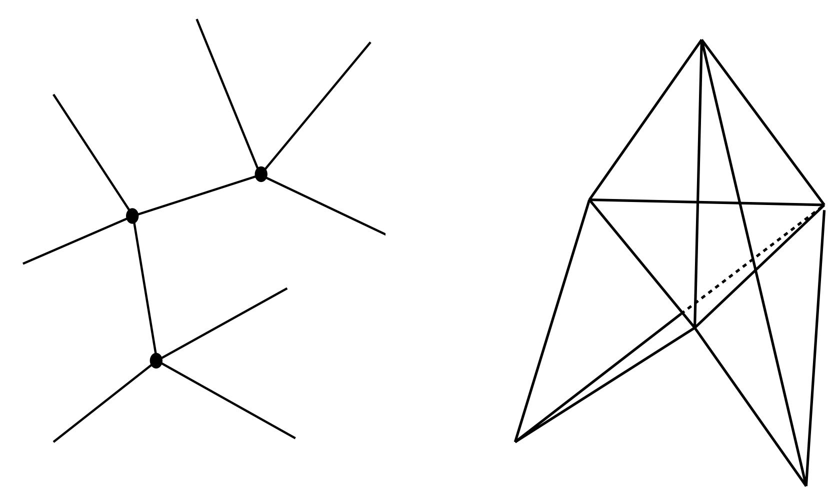
$$\mathcal{H}_\gamma = L^2\left(G^E/G^V, d\mu = \prod_{e=1}^{E} d\mu_e^{Haar}\right)$$

G= SU(2)



spin networks can be understood as (generalised) piecewise-flat discrete geometries

underlying graphs are dual to (simplicial lattices)



Geometric observables correspond to operators; some of them have discrete spectrum: discretization of quantum geometry! (Rovelli, Smolin, Ashtekar, Lewandowski, 1995-1997)

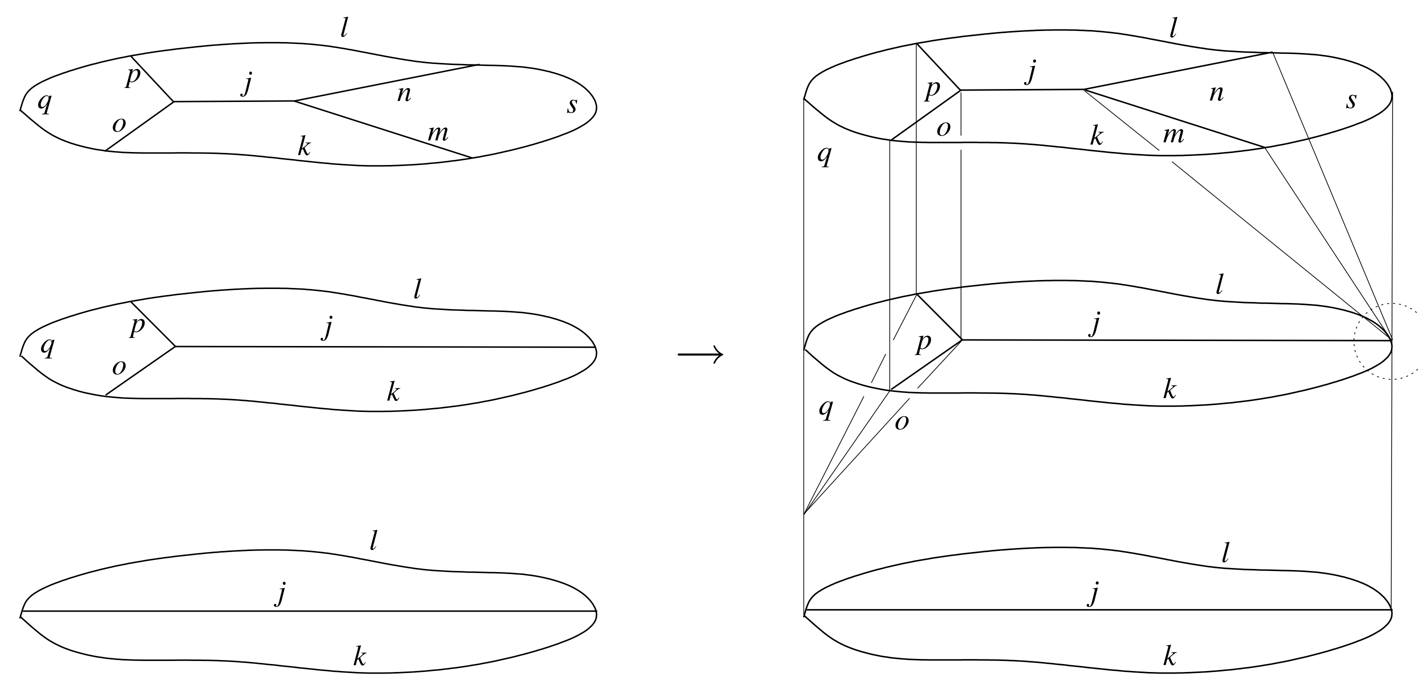
$$\hat{A}\, |\bigcirc_j\rangle = 8\pi\beta l_p^2 \sqrt{j(j+1)}\, |\bigcirc_j\rangle$$

Loop Quantum Gravity (and spin foam models)

M. Reisenberger, C. Rovelli, J. Baez, J. Barrett, L. Crane, A. Perez, E. Livine, DO, S. Speziale, ……

evolution of spin networks involves changes in combinatorial structure and in algebraic labels

"histories" (dynamical interaction processes) are also purely algebraic and combinatorial: spin foams



purely algebraic and combinatorial "path integral for quantum gravity"

$$\langle \Psi_\gamma(j,i) \,|\, \Psi_{\gamma'}(j',i') \rangle = \sum_{\Gamma|\gamma,\gamma'} w(\Gamma) \sum_{\{J\},\{I\}|j,j',i,i'} \mathcal{A}_\Gamma(J,I) \approx \text{"} \int \mathcal{D}g \, e^{i\,S(g)} \text{"}$$

spin networks/spin foams can be understood as (generalised) piecewise-flat discrete geometries

the underlying graphs and 2-complexes are dual to (simplicial) lattices

Lots of results on quantum geometry and mathematics of quantum gravitational field; inspiring models of quantum black holes and quantum cosmology

New perspective: emergent spacetime and gravity

- failures of GR and QFT at high energies/small distances   breakdown of continuum spacetime itself?

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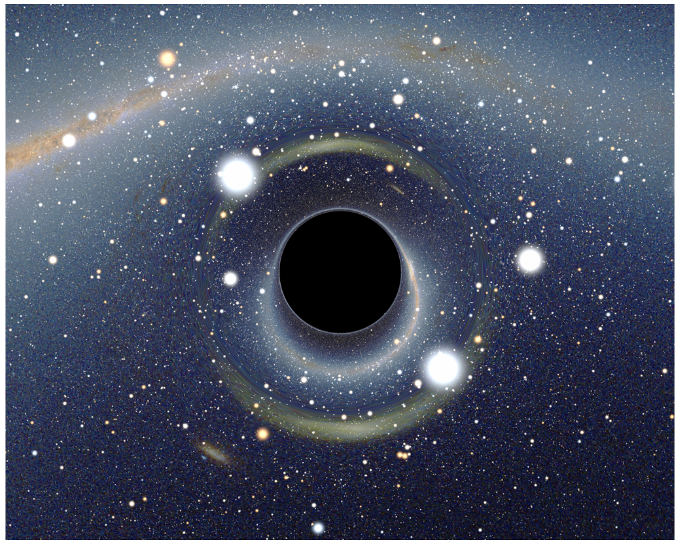
- black hole thermodynamics

J. Bekenstein, S. Hawking, ……



$$S = \frac{1}{4}\frac{c^3}{\hbar G}A$$

solution of information loss paradox require non-locality?

$$T = \frac{\hbar c^3}{8\pi k G M}$$

if spacetime itself has entropy, it has microstructure
if entropy is finite, this implies discreteness

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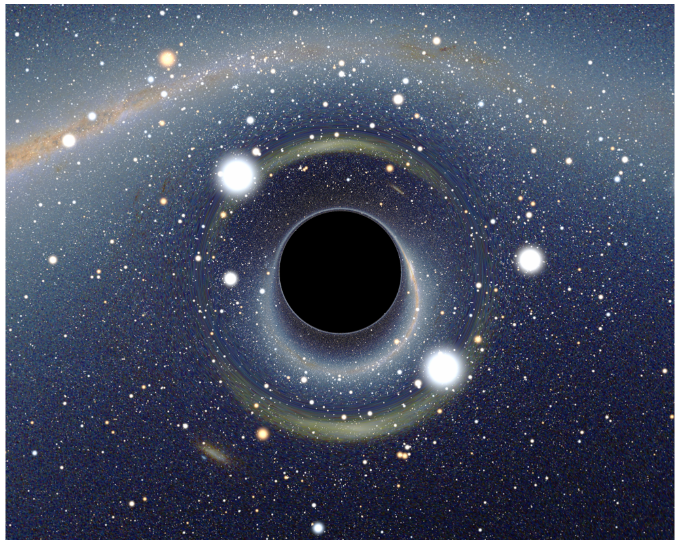
- failures of GR and QFT at high energies/small distances — breakdown of continuum spacetime itself?



- black hole thermodynamics — J. Bekenstein, S. Hawking, ……

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if entropy is finite, this implies discreteness

- Einstein's equations as equation of state — T. Jacobson, ….., T. Padmanabhan, ……

$$\delta Q = T dS$$

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

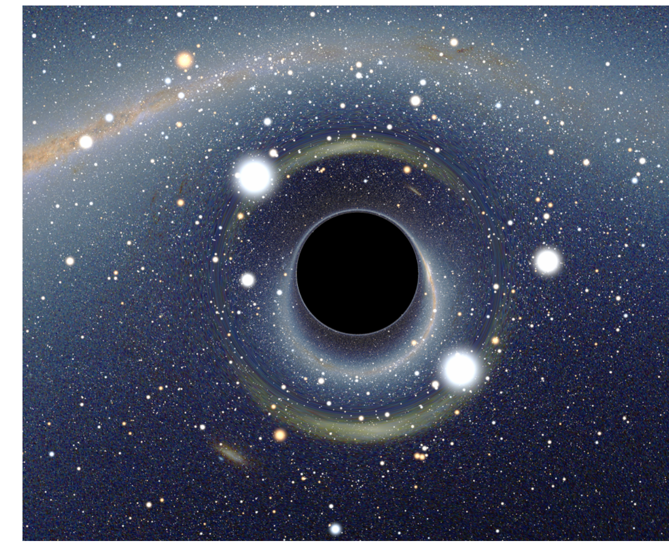
IDEA	**geometric entropy functional**	**+**	**local matter-energy perturbations**	**=>**	**Einstein eq. as equation of state**

crucial: "holographic" behaviour

$$\delta S = \alpha\, \delta A$$

New perspective: emergent spacetime and gravity

- failures of GR and QFT at high energies/small distances — breakdown of continuum spacetime itself?



- black hole thermodynamics — J. Bekenstein, S. Hawking, ……

$$S = \frac{1}{4}\frac{c^3}{\hbar G} A$$

solution of information loss paradox require non-locality?

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effective curved metric and matter fields from non-geometric atomic theory

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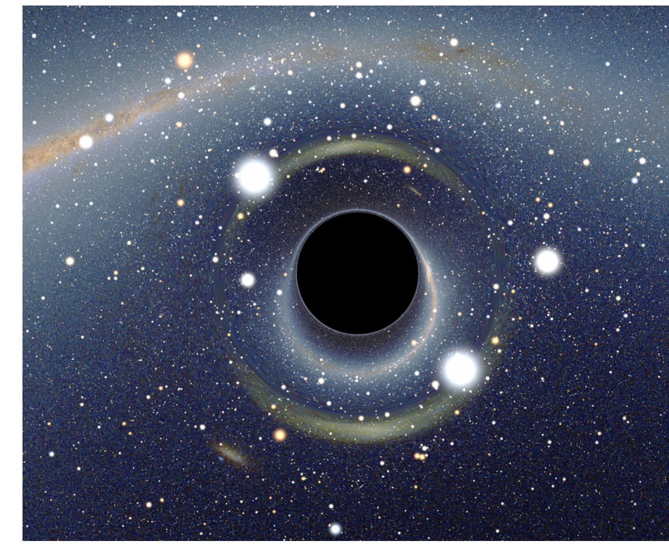

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Is gravity an emergent phenomenon?
Are spacetime and fields just collective emergent entities?

suggested also by modern QG approaches - new non-spatiotemporal dofs

Quantum Gravity:
(possible) phenomenology

QG phenomenology

many (simplified) scenarios are already testable

- minimal length
- deformed uncertainty relations

$$[X, P] = i\hbar\,(1 + \tau P^2)$$

- violation/deformation of spacetime symmetries (e.g. Lorentz symmetry)

G. Amelino-Camelia, '08

S. Hossenfelder, '12

T. Jacobson, S. Liberati, D. Mattingly, '07

QG modification of effective field theory

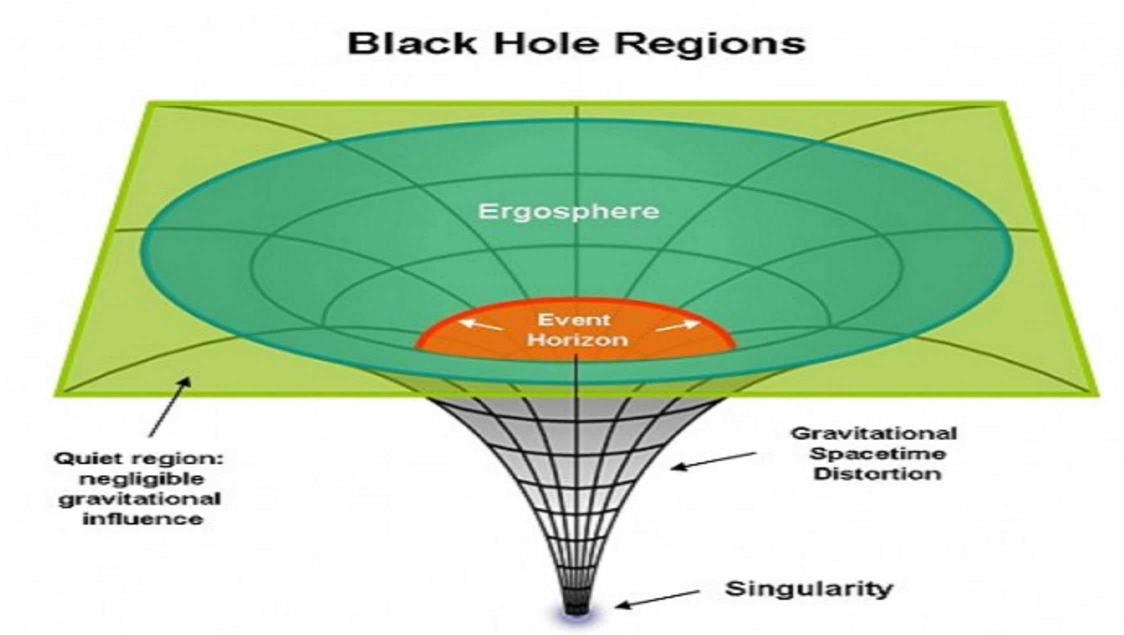
- modified dispersion relations

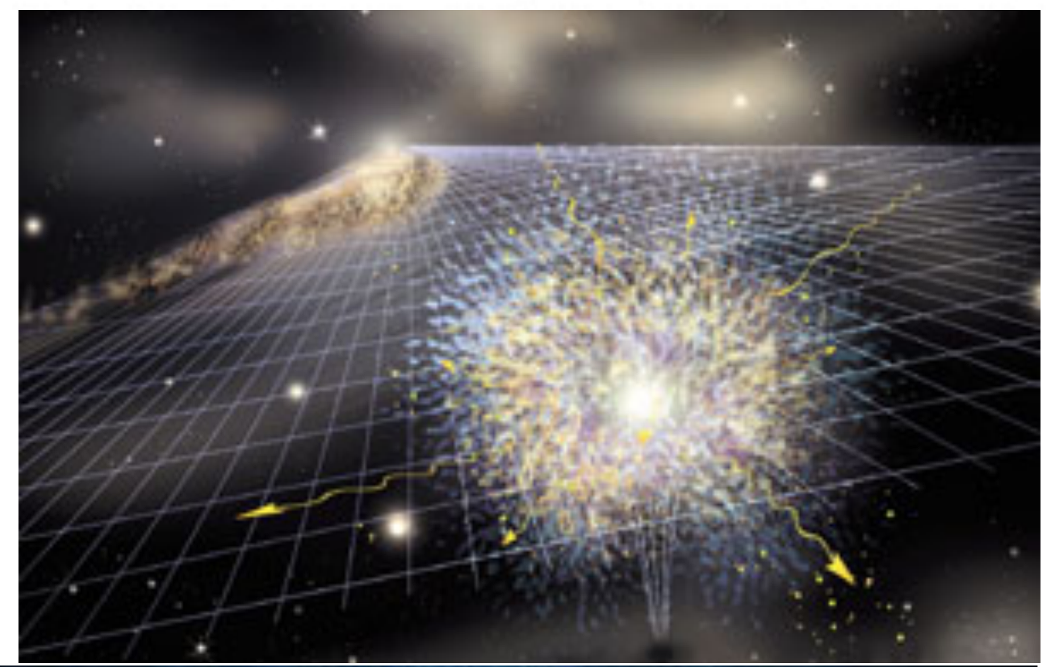
$$m^2 \approx E^2 - \vec{p}^2 + \alpha\left(\frac{E}{m_{\mathrm{P}}}\right)E^2$$

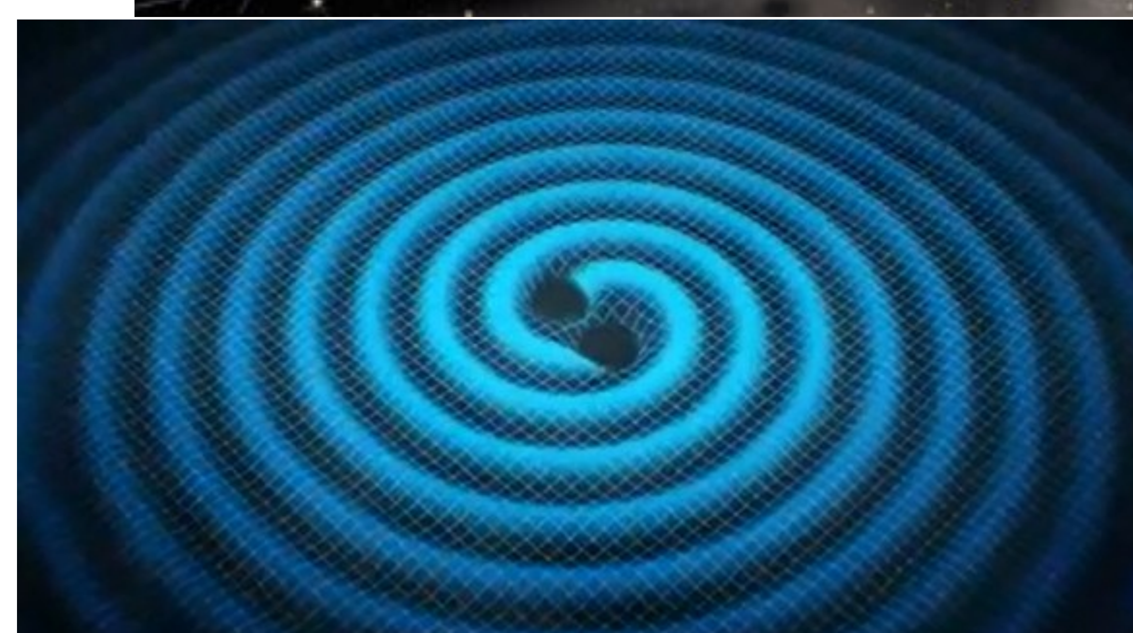
- modified scattering thresholds
- non-local terms (violation of locality)

QG effects in black hole physics

- Hawking radiation and BH evaporation
    - reviation from thermal radiation?
    - end result: compact remnant? nothing?
    - black hole information paradox (is unitarity violated? renounce locality?)
- BH formation, horizon and singularity
    - regular black hole-like objects in QG (with “horizon”, but no singularity)
        - inner quantum region A. Ashtekar, M. Bojowald, ….
        - black hole -> white hole transition (radio bursts) H. Haggard, C. Rovelli, F. Vidotto, …
    - exotic compact objects
        - horizonless - imperfect absorption (modified GW signal) V. Cardoso, P. Pani ….
        - outer “membrane” - GW echo J. Abedi, H. Dykaar, N. Afshordi, ‘16





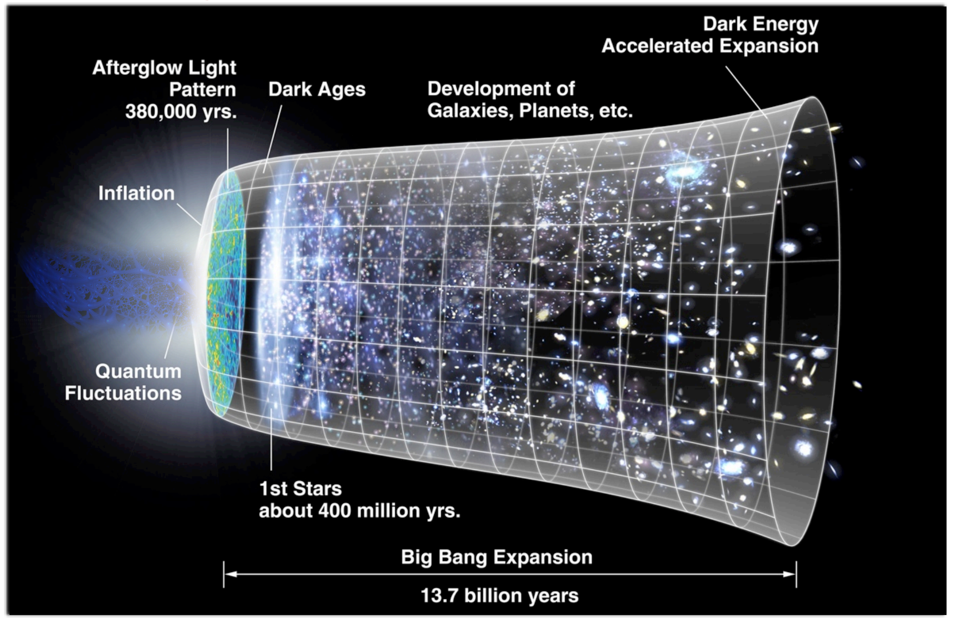


QG in cosmological scenarios for the early universe

why a close to homogeneous and isotropic universe?

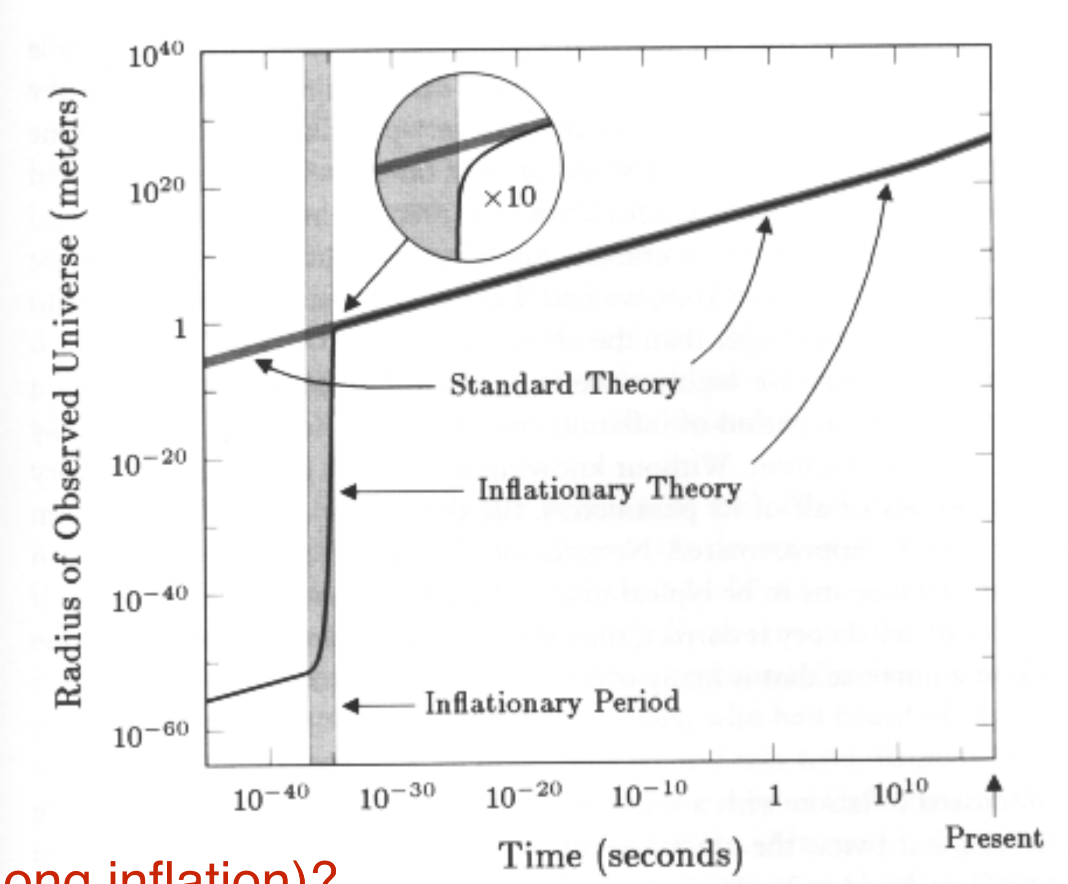
why an approximately scale invariant power spectrum?

R. Brandenberger, '10, '11, '14



Inflation

- density perturbations as vacuum quantum fluctuations
- period of accelerated expansion (driven by "inflaton" field?)
- naturally scale invariant spectrum



Bouncing cosmology

- what produces inflation?
- physics of trans-Planckian modes (for long inflation)?
- inflation too close to Planck regime?
- inflationary spacetime still contains singularity

Emergent universe

Inflation needs Quantum Gravity

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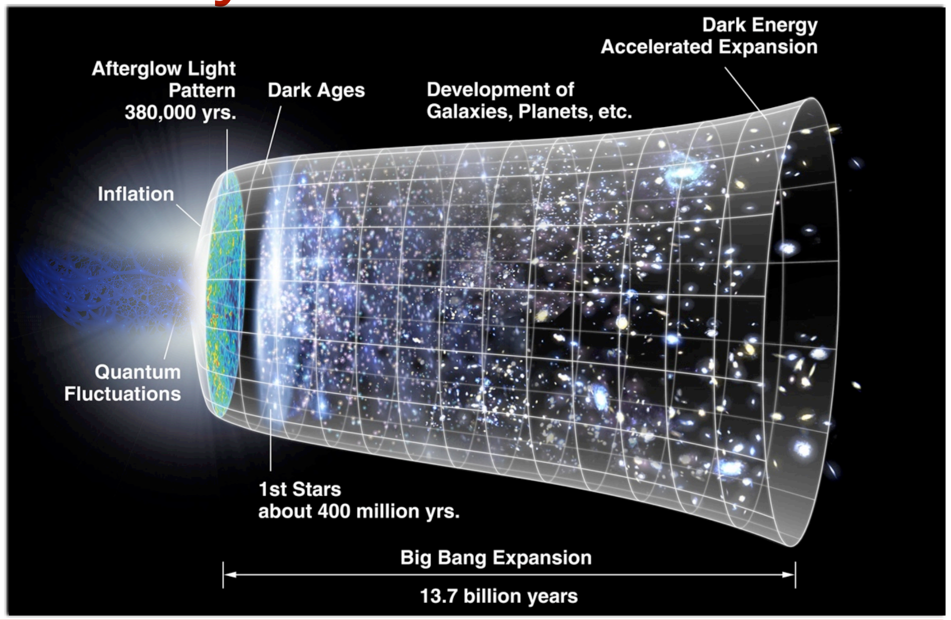
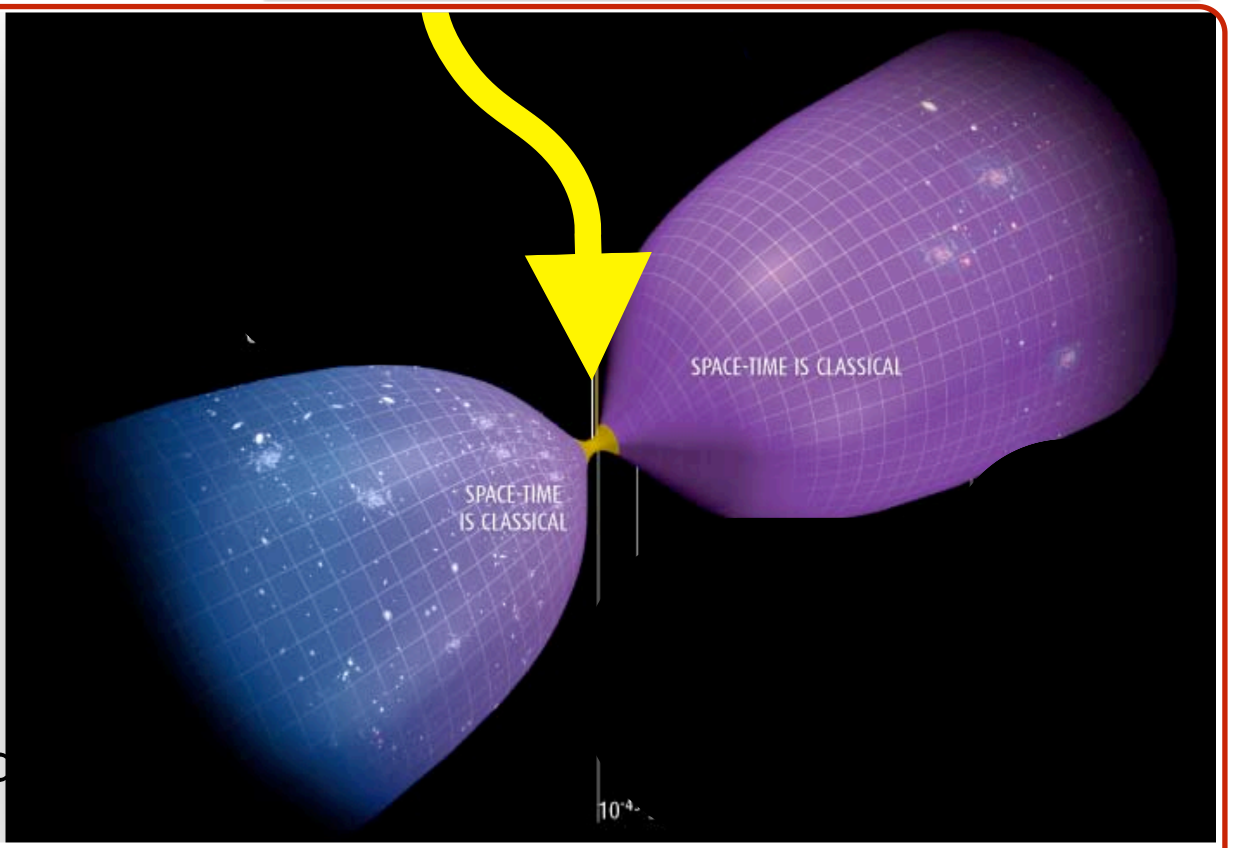


Inflation

Bouncing cosmology

- classical contracting phase “before” the big bang, bouncing to current expanding phase
- various realizations (e.g. LQC)
- can produce scale invariant spectrum
- trans-Planckian modes not needed



- new physics needed to describe/justify cosmological bounce

Bouncing cosmology needs Quantum Gravity

Emergent universe

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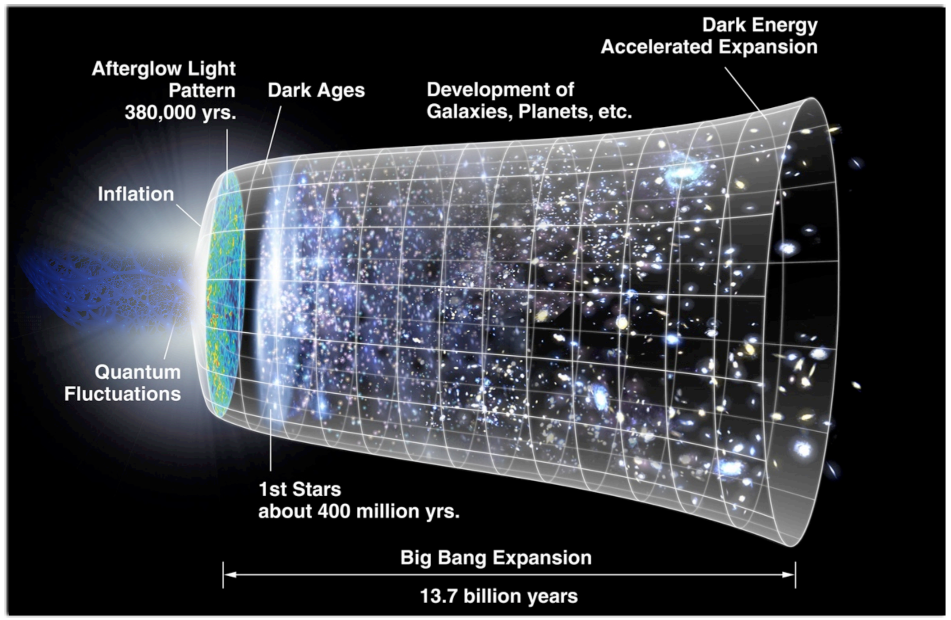
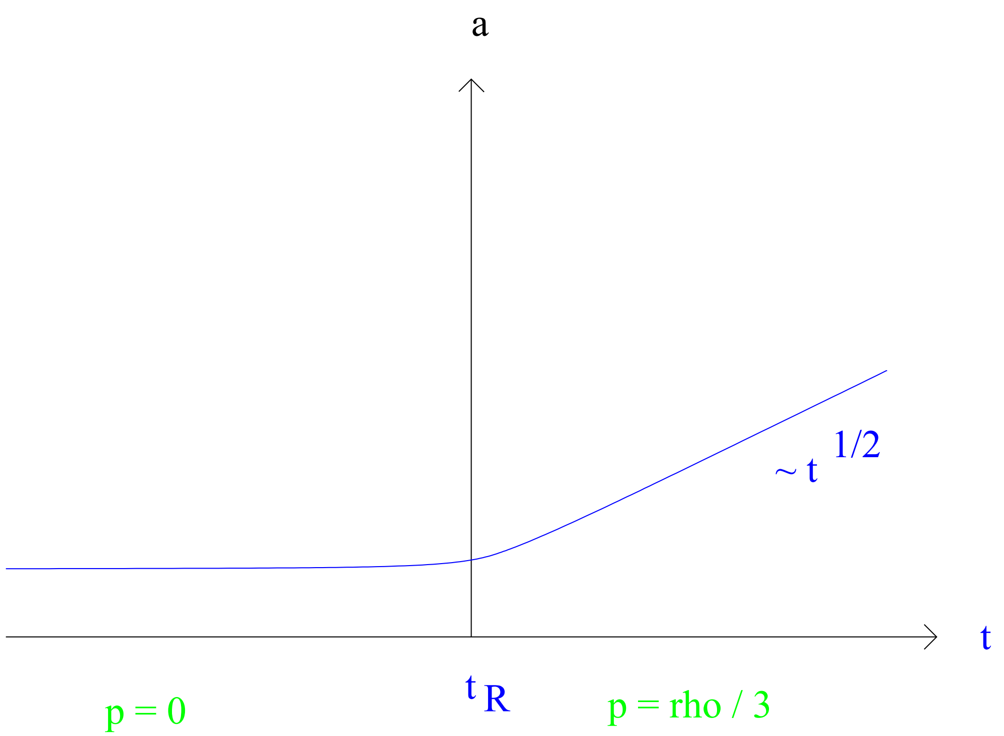


Inflation

Bouncing cosmology

Emergent universe

- phase transition between static and expanding universe
- various realizations (e.g. string gas cosmology)
- density perturbations as thermal fluctuations
- can give scale invariant power spectrum
- trans-Planckian modes not needed
- static phase and phase transition require new physics



Emergent universe needs Quantum Gravity

QG effects in emergent gravity scenarios

Verlinde's emergent gravity

E. Verlinde, '16, S. Hossenfelder, '17

gravity as eqn of state

+

modified entropy formula (new volume-dependent term, akin to dark energy)

$\longrightarrow$

modified gravity to explain dark matter (new acceleration scale ~ MOND)

proposals for cosmological constant/dark energy

non-local gravity (continuum only approximate; also from other perspectives) C. Wetterich, '97;...; M. Maggiore, '17

suggestions from analogue gravity models (e.g. cosmological constant from depletion factor if spacetime is Bose condensate) S. Finazzi, S. Liberati, L. Sindoni, '12

vanishing vacuum energy from global equilibrium of spacetime fluid G. Volovik, '01, '05, '11

new dissipative effects in dispersion relations

S. Liberati, L. Maccione, '13

if spacetime is like fluid or superfluid medium, should expect dissipation

manifest in dispersion relations $$\omega^2 \simeq c^2 k^2 \left[1 - i\frac{4}{3}\frac{\nu k}{c} - \frac{8}{9}\left(\frac{\nu k}{c}\right)^2 + i\frac{8}{27}\left(\frac{\nu k}{c}\right)^3\right]$$

QG effects (potentially) testable

despite suppression by Planck scale

Main theoretical problem:

most testable effects obtained within simplified models and phenomenological frameworks

very weak link with fundamental theory

no real control over approximations and assumptions

pressing issue:
connect simplified models with fundamental formalisms

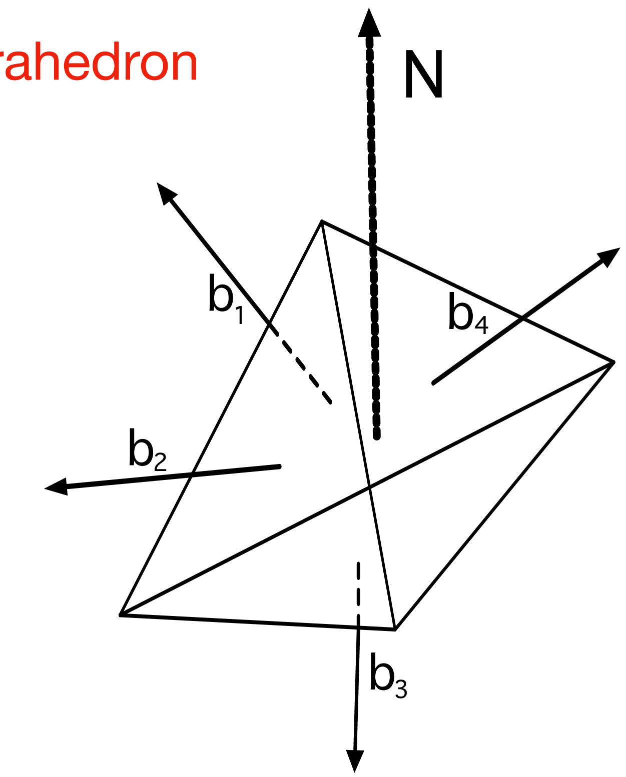
Group field theory:

an example of fundamental quantum gravity formalism

An “atom of space”

Barbieri ’97; Baez, Barrett, ’99; Rovelli, Speziale, ’06; Bianchi, Dona, Speziale, ’10; ……

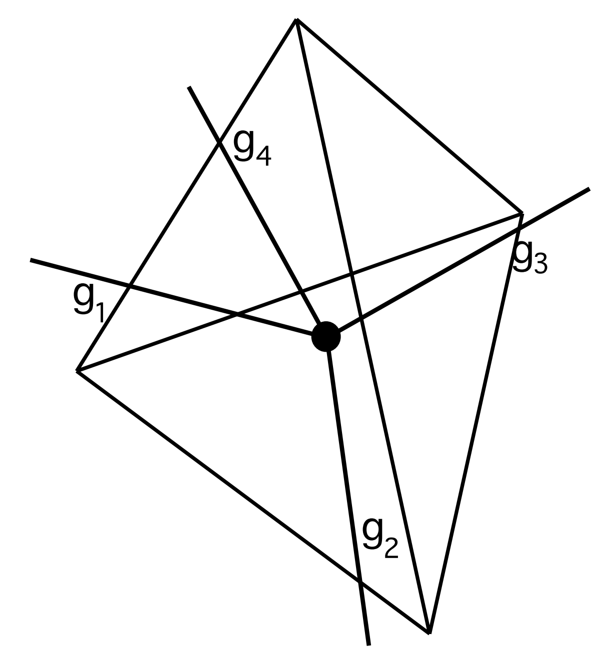
Elementary building block of 3d space: single polyhedron - simplest example: a tetrahedron



Classical geometry in group-theoretic variables

4 vectors normal to triangles that close (lying in hypersurface with normal N)

$$\boxed{A_i\, n_i^I \;=\; b_i^I \in \mathbb{R}^{3,1} \qquad b_i \cdot N \;=\; 0 \qquad \sum_i b_i \;=\; 0}$$



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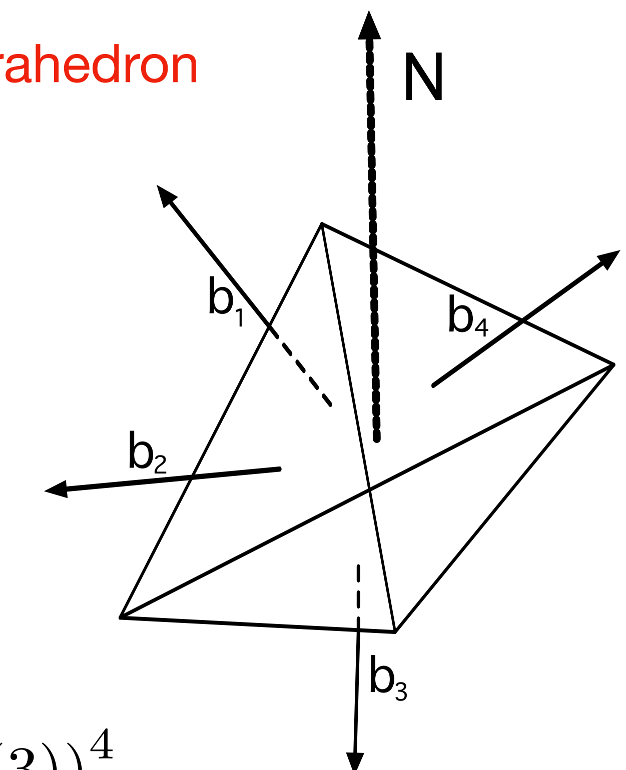

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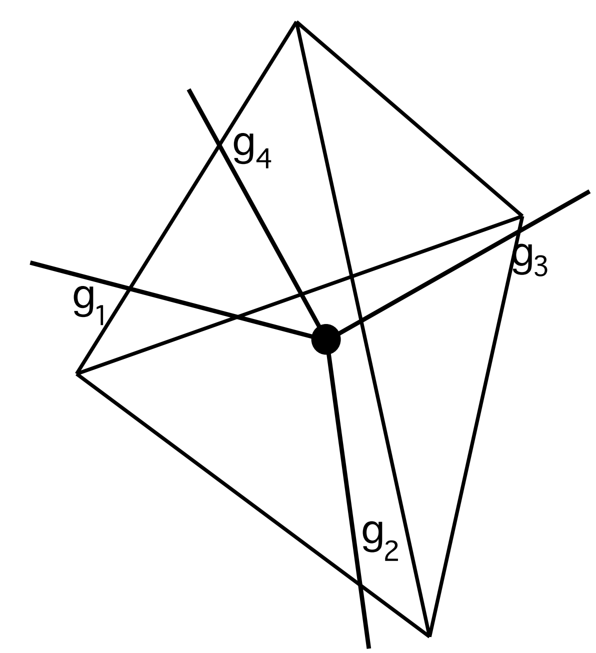
phase space:

$$(\mathcal{T}^* SO(3,1))^4 \simeq (\mathfrak{so}(3,1) \times SO(3,1))^4 \supset (\mathfrak{so}(3) \times SO(3))^4 \simeq (\mathcal{T}^* SO(3))^4$$



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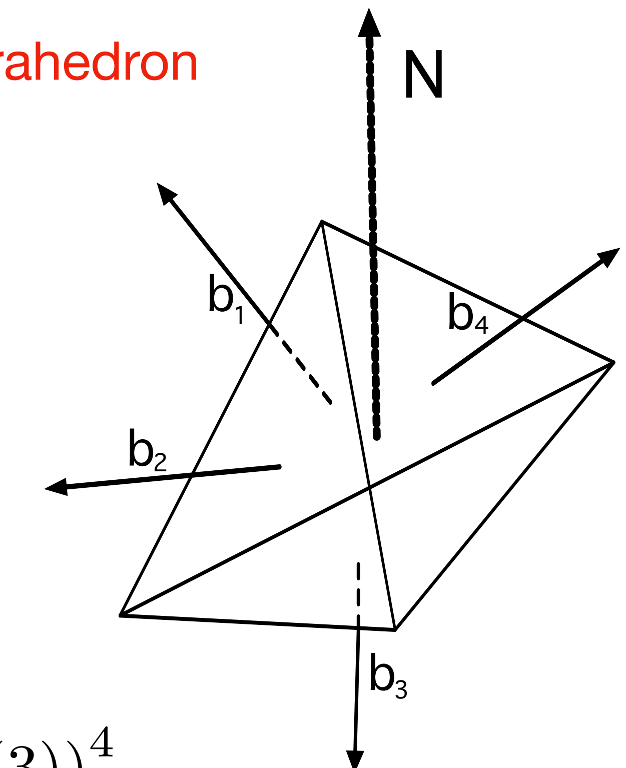

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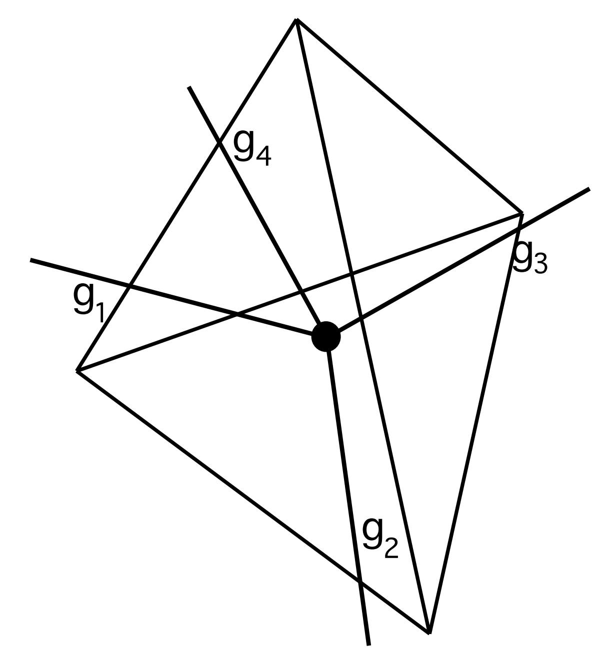

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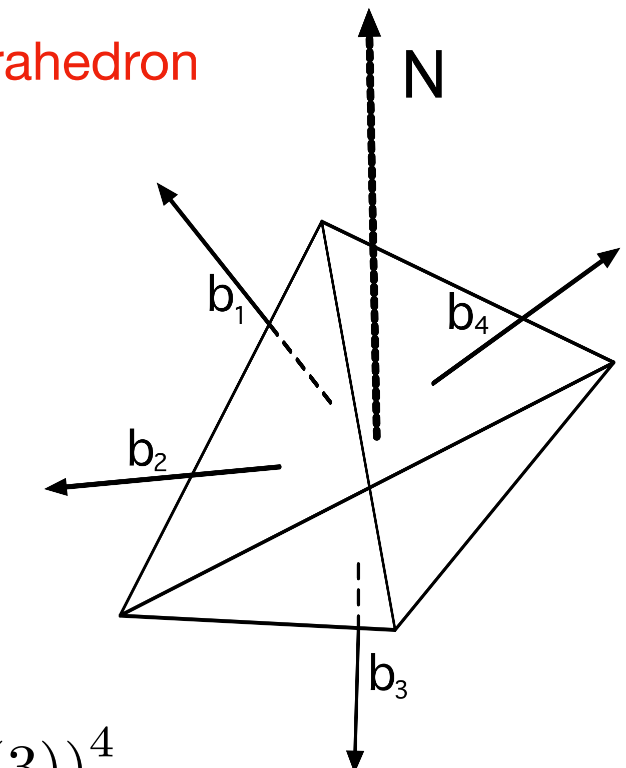

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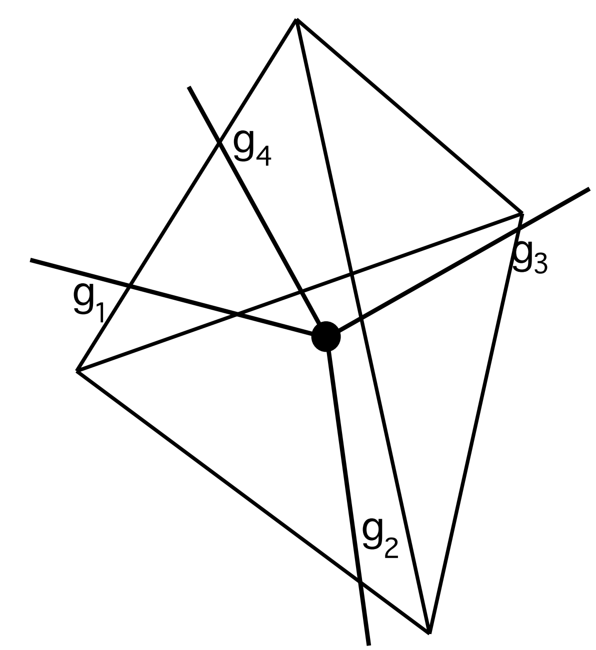
general: $(\mathcal{T}^* G)^{\times d} \simeq (\mathfrak{g} \times G)^{\times d}$



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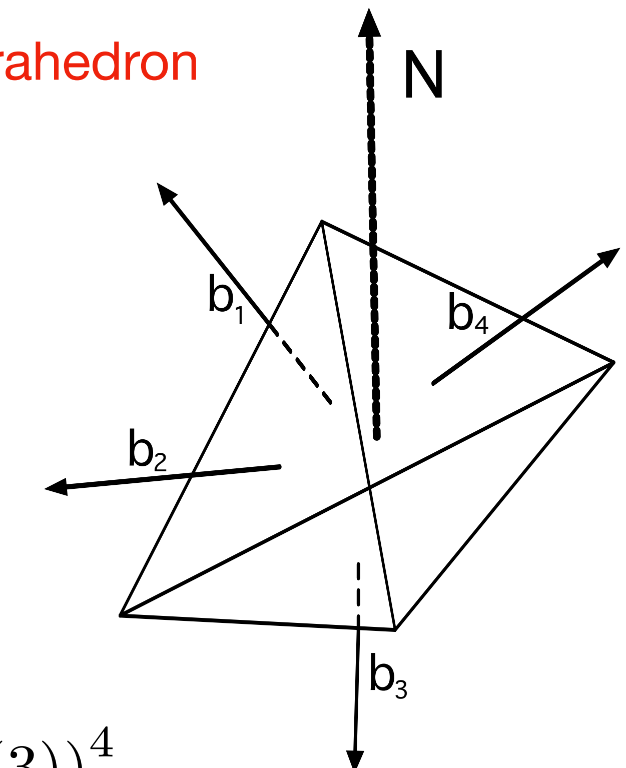

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Quantum geometry in group-theoretic variables

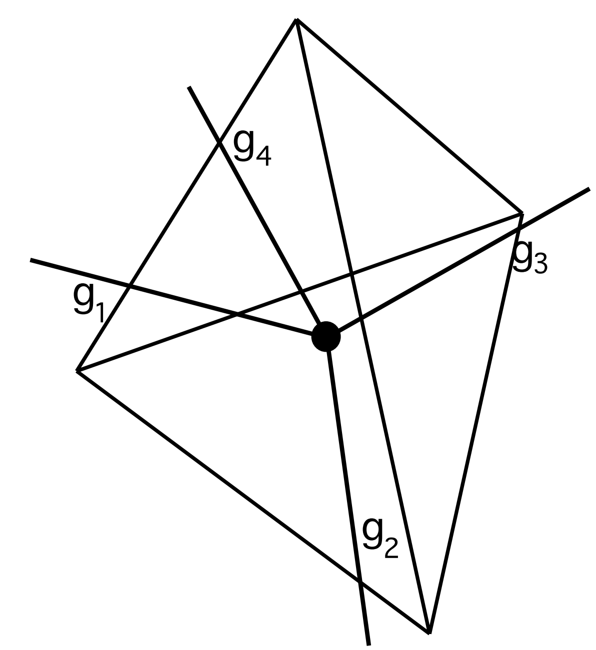
Hilbert space

$$\mathcal{H}_v \;=\; L^2\left(G^d; d\mu_{Haar}\right)$$

+ constraints on states

$$B_i^{IJ} \;\rightarrow\; \hat{J}^{IJ} \in \mathfrak{so}(3,1) \qquad b_i^J \;\rightarrow\; \hat{J}_N^i \;\in \mathfrak{su}(2)$$

spin network vertex



Quantum space as a many-body system

DO, ‘13

Many-body Hilbert space for “quantum space”: Fock space

$$\mathcal{F}(\mathcal{H}_v) = \bigoplus_{V=0}^{\infty} sym\left\{\left(\mathcal{H}_v^{(1)} \otimes \mathcal{H}_v^{(2)} \otimes \cdots \otimes \mathcal{H}_v^{(V)}\right)\right\}$$

Fock vacuum: “no-space” state $|0>$

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Second-quantised representation: ladder and geometric operators

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e.g. total space volume (extensive quantity):

$$\hat{V}_{tot} = \int [dg_i][dg'_j] \hat{\varphi}^{\dagger}(g_i) \, V(g_i, g'_j) \, \hat{\varphi}(g'_j) = \sum_{J_i} \hat{\varphi}^{\dagger}(J_i) \, V(J_i) \, \hat{\varphi}(J_j)$$

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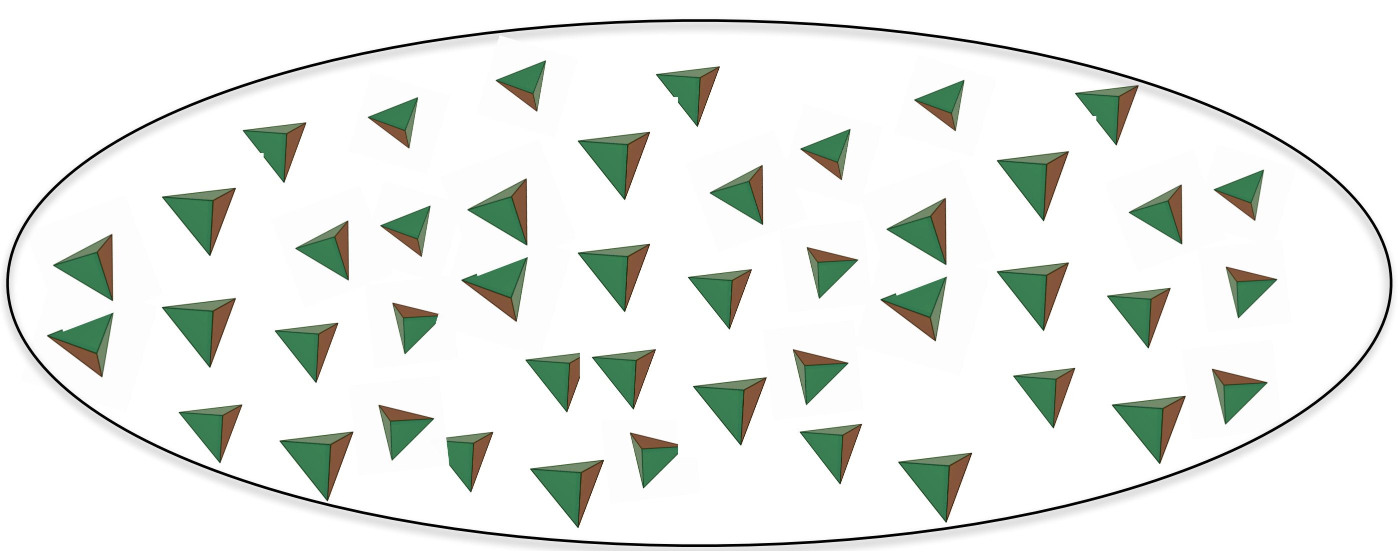
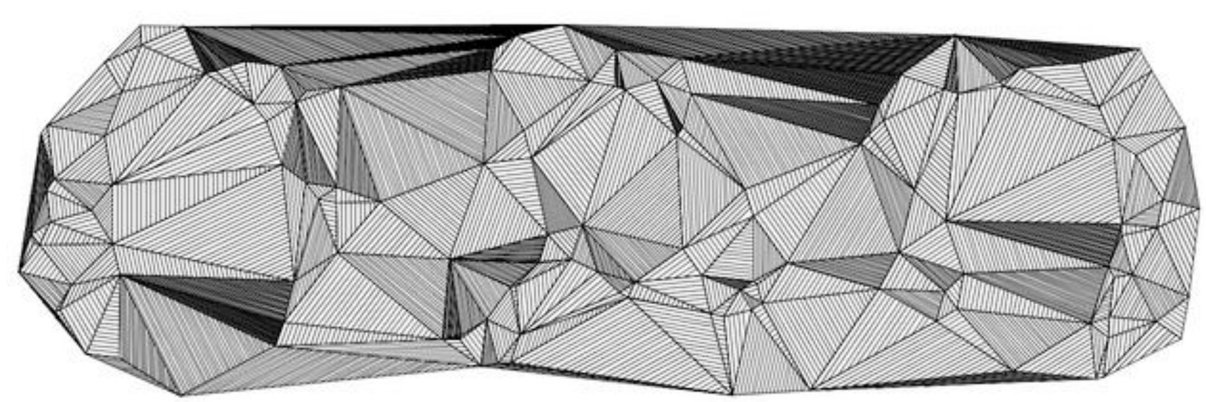
Quantum space as an system of many quantum polyhedra/spin network vertices

generic states not very “spacey” at all - “connected” many-body states a little more “spacey”



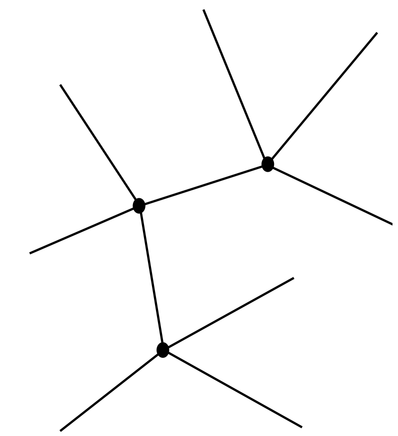


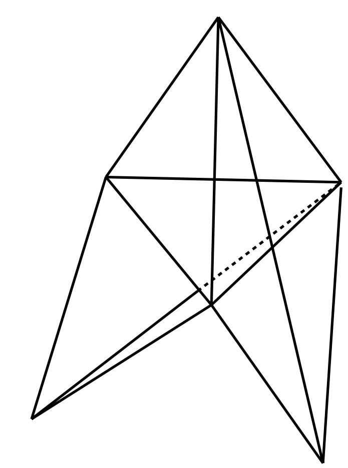
Quantum space as a many-body system

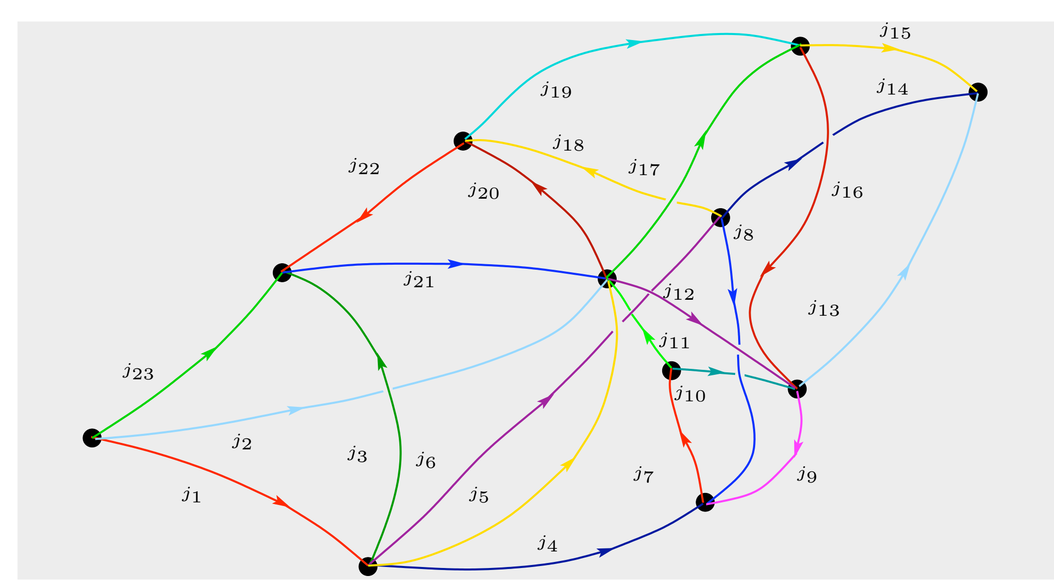
DO, ‘13

Forming extended structures: gluing building blocks — —-> states on connected graphs/simplicial complexes

$$\mathcal{H}_\gamma \subset \mathcal{H}_V \qquad \Psi\gamma(G_{ij}^{ab}) = \prod_{[(ia),(jb)]} \int_G d\alpha_{ij}^{ab}\, \phi_V(\ldots, g_{ia}\,\alpha_{ij}^{ab}, \ldots, g_{jb}\alpha_{ij}^{ab}, \ldots) = \Psi\gamma(g_{ia}(g_{jb})^{-1})$$







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DO, '13

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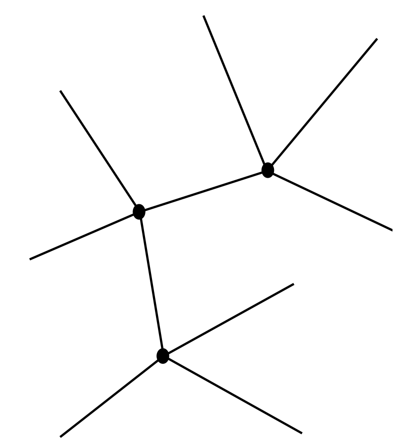
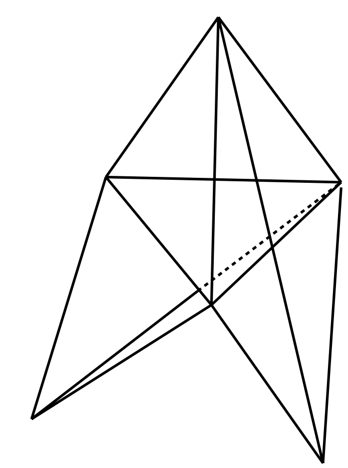
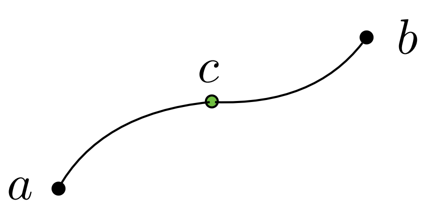


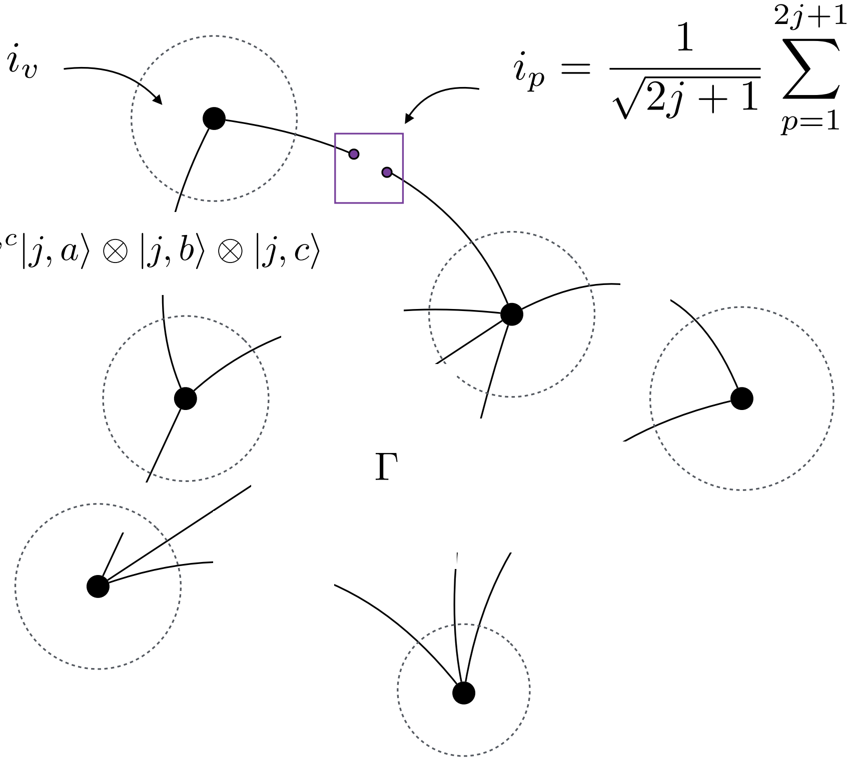
Gluing = connectivity = entanglement between "atoms of space"





$$= \frac{1}{\sqrt{2j+1}} \sum_{c=1}^{2j+1} \langle U|\gamma_1, j, a, c\rangle\, \langle U|\gamma_2, j, c, b\rangle$$

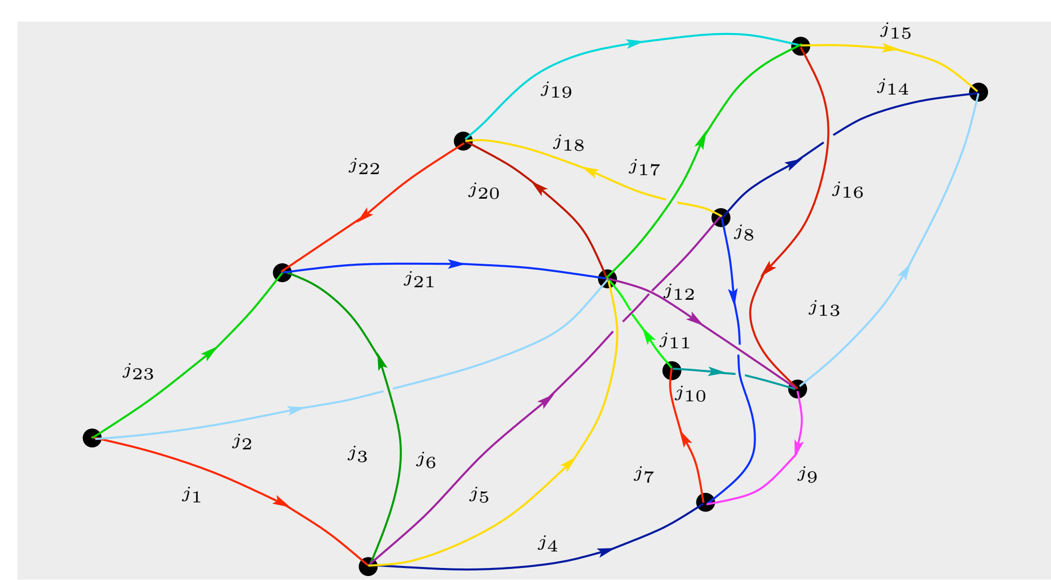
maximally mixed state



$$i_p = \frac{1}{\sqrt{2j+1}} \sum_{p=1}^{2j+1} |e_p\rangle\langle e_p|$$

$$|\mathcal{I}\rangle = \sum_{\{a,b,c\}} i^{a,b,c} |j,a\rangle \otimes |j,b\rangle \otimes |j,c\rangle$$

Donnelly, '12; Livine, Terno, '08;
Chirco, Mele, DO, Vitale, '17



Dynamics of quantum space as a group field theory

DO, ’09; DO, ‘14

Dynamics governs gluing processes and formation of extended discrete structures

Interactions processes correspond to (simplicial) complexes in one dimension higher

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"combinatorial non-locality"
in pairing of field arguments

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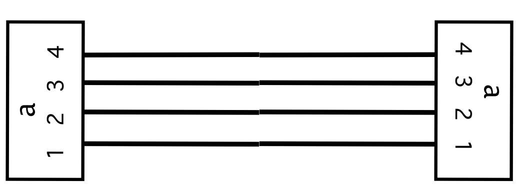
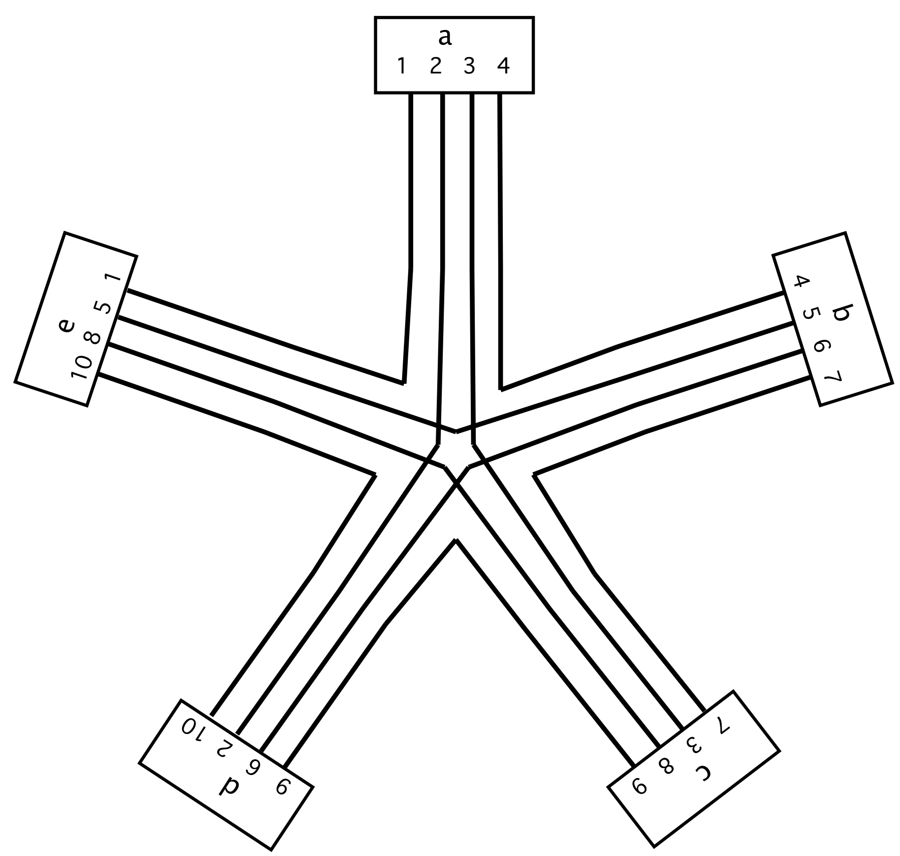
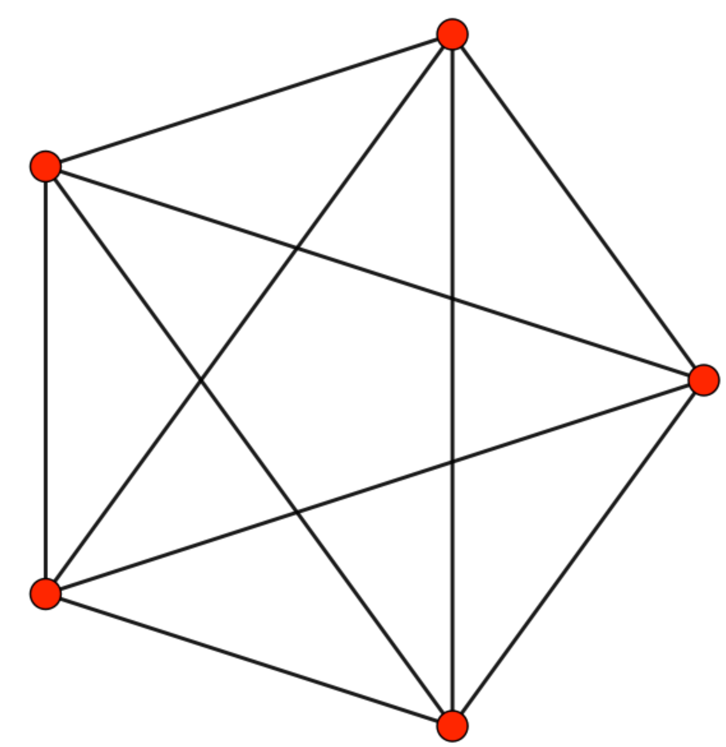
Example: simplicial interactions







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

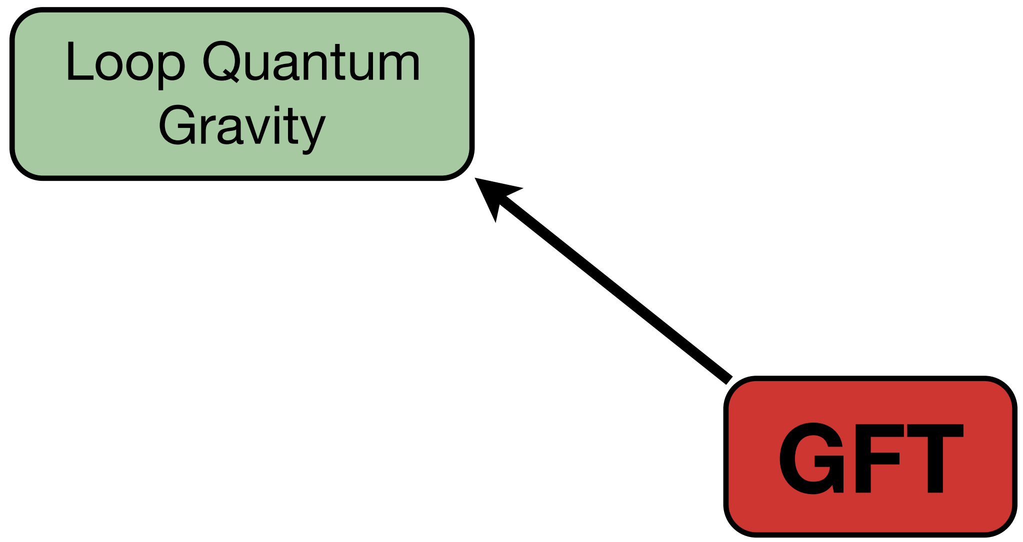
Feynman diagrams = stranded diagrams dual
to cellular complexes of arbitrary topology

sum over triangulations/complexes

amplitude for each
triangulation/complex

Dynamics of quantum space as a group field theory

Multiple relations with other QG formalisms



GFT and Loop Quantum Gravity

DO, ’13; DO, ‘14

Quantum dofs are same as in LQG (spin networks), organised in different (but similar) Hilbert space

2nd quantized reformulation of states and dynamics

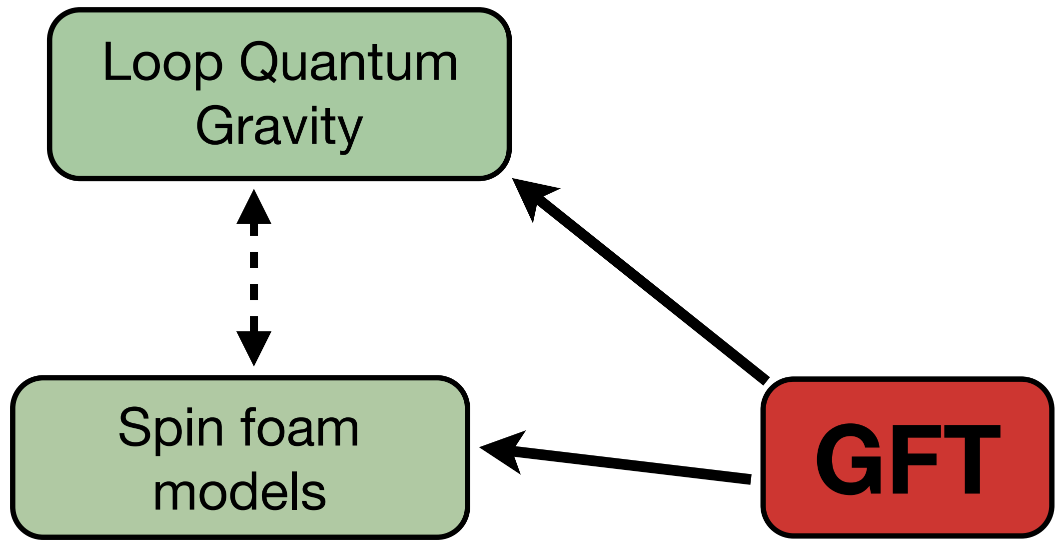
$$\mathcal{H}_\gamma \subset \mathcal{H}_V \qquad \Psi\gamma(G_{ij}^{ab}) = \prod_{[(ia),(jb)]} \int_G d\alpha_{ij}^{ab}\, \phi_V(\ldots, g_{ia}\, \alpha_{ij}^{ab}, \ldots, g_{jb}\alpha_{ij}^{ab}, \ldots) = \Psi\gamma(g_{ia}(g_{jb})^{-1})$$

$$\widehat{\mathcal{O}_{n,m}} \quad \to \quad \langle \vec{\chi}_1, ..., \vec{\chi}_m | \widehat{\mathcal{O}_{n,m}} | \vec{\chi}'_1, ..., \vec{\chi}'_n \rangle = \mathcal{O}_{n,m}\left(\vec{\chi}_1, ..., \vec{\chi}_m, \vec{\chi}'_1, ..., \vec{\chi}'_n\right) \qquad \to$$

$$\to \quad \widehat{\mathcal{O}_{n,m}}\left(\hat{\varphi}, \hat{\varphi}^\dagger\right) = \int [d\vec{g}_i][d\vec{g}'_j]\; \widehat{\varphi}^\dagger(\vec{g}_1)..\widehat{\varphi}^\dagger(\vec{g}_m) \mathcal{O}_{n,m}\left(\vec{g}_1, .., \vec{g}_m, \vec{g}'_1, .., \vec{g}'_n\right) \widehat{\varphi}(\vec{g}'_1)..\widehat{\varphi}(\vec{g}'_n)$$

Dynamics of quantum space as a group field theory

Multiple relations with other QG formalisms



GFT and spin foam models

$$Z(\Gamma) \leftrightarrow \begin{cases} A_f(J) \\ A_e(J,I) \\ A_v(J,I) \end{cases}$$

Reisenberger, Rovelli, '00

$$\begin{cases} \mathcal{K}(J,I) \sim \mathcal{K}(g) \\ \mathcal{V}(J,I) \sim \mathcal{V}(g) \end{cases} \quad \leftrightarrow \quad S(\varphi,\bar{\varphi})$$

Spin foam model = quantum amplitude for spin network evolution

$$Z(\Gamma) = \sum_{\{J\},\{I\}|j,j',i,i'} \prod_f A_f(J,I) \prod_e A_e(J,I) \prod_v A_v(J,I)$$

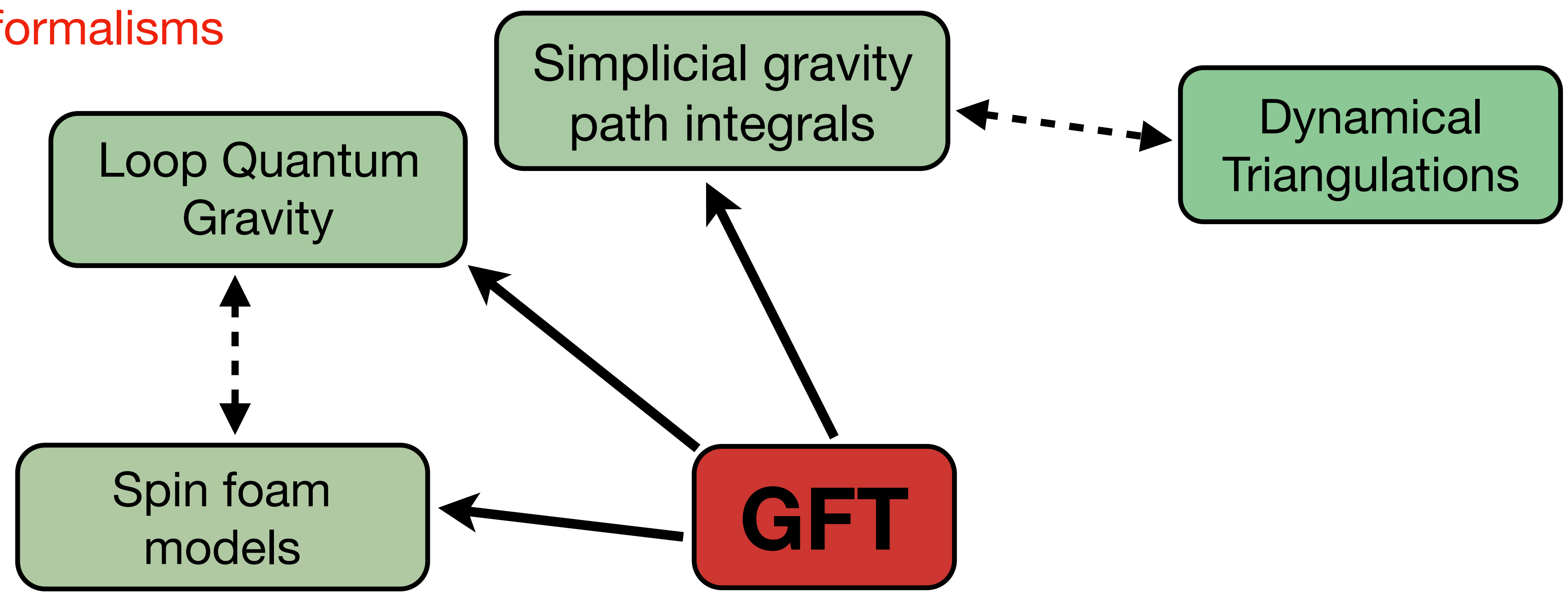
Any spin foam amplitude is the Feynman amplitude of a GFT model

$$S(\varphi,\overline{\varphi}) = \frac{1}{2}\int [dg_i]\overline{\varphi(g_i)}\mathcal{K}(g_i)\varphi(g_i) + \frac{\lambda}{D!}\int [dg_{ia}]\varphi(g_{i1})....\varphi(\bar{g}_{iD})\mathcal{V}(g_{ia},\bar{g}_{iD}) \quad + \quad c.c.$$

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

Dynamics of quantum space as a group field theory

Multiple relations with other QG formalisms



GFT and simplicial gravity path integrals

GFT Feynman amplitudes (model-dependent):
lattice gravity path integrals
(with group+Lie algebra variables)
on the lattice defined by the Feynman diagram

Baratin, DO, '11

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

$$= \sum_\Delta w(\Delta)\, \mathcal{A}_\Delta = \sum_\Delta w(\Delta) \int \mathcal{D}g_\Delta \; e^{i\, S_\Delta(g_\Delta)} \equiv \int \mathcal{D}g \; e^{i\, S(g)}$$

dynamical triangulations + quantum Regge calculus

Dynamics of quantum space as a group field theory

Application of QFT tools to QG problems: GFT renormalization

Ben Geloun, Benedetti, Bonzom, Carrozza, Dittrich, DO, Einchhorn, Gurau, Koslowski, Krajewski, Lahoche, Ousmane Samary, Riello, Rivasseau, Tanasa, Toriumi, Vitale, …

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Issue 1: construction and quantisation ambiguities in definition of GFT models

Issue 2: continuum limit: controlling quantum dynamics of many interacting QG dofs

- GFT perturbative renormalization

—-> renormalizability of GFT model

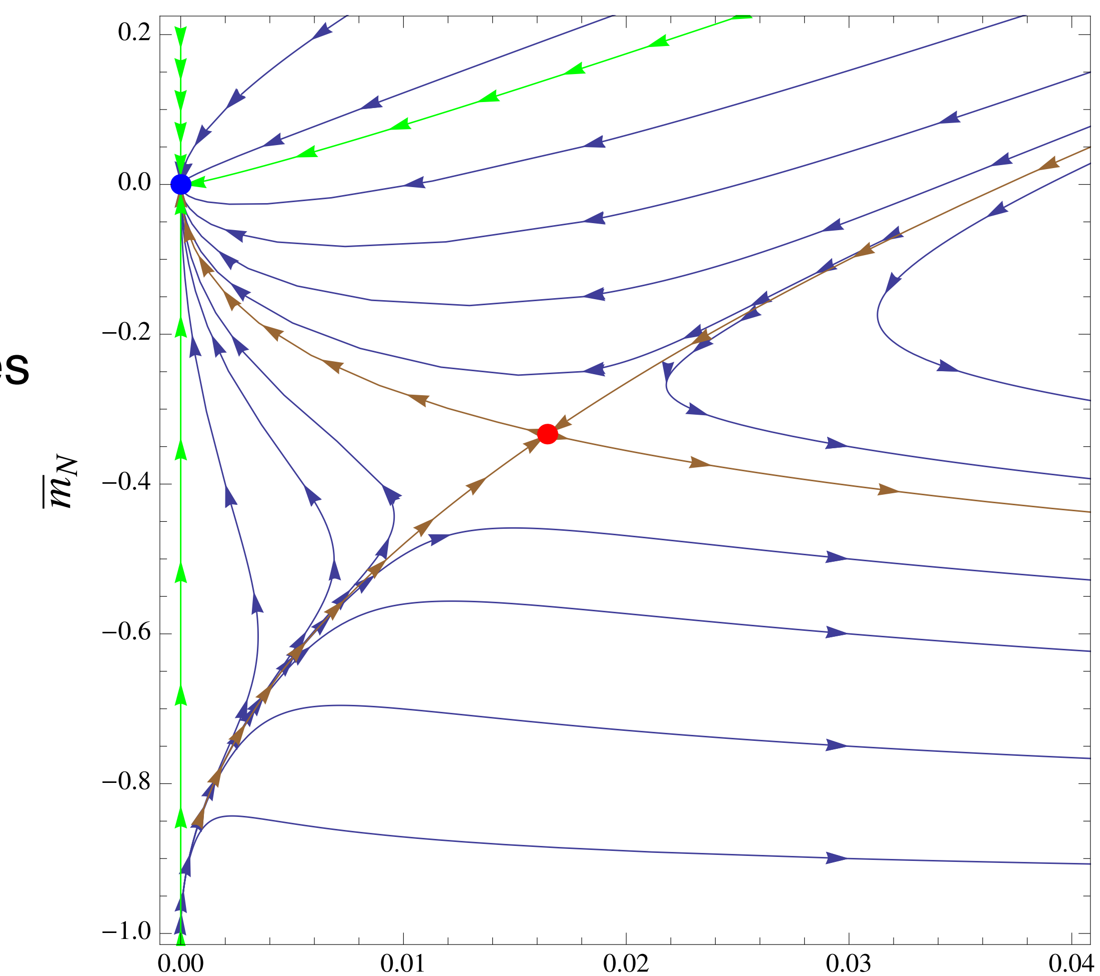
- GFT non-perturbative renormalization

——> RG flow ~ full GFT partition function & continuum phases

general strategy:

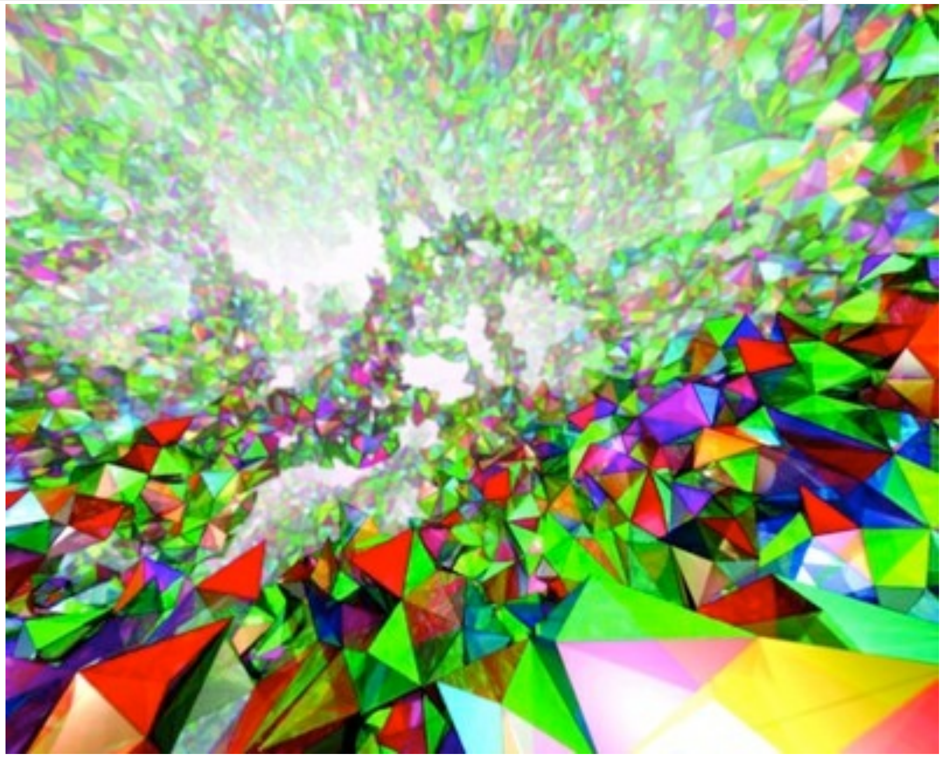
treat GFTs as ordinary QFTs defined on Lie group manifold

- Divergences in simplicial models
- Renormalizability of TGFT models (d>2, non-abelian, w gauge invariance, ….)
- Generic asymptotic freedom/safety, hints of condensed phase, WF fixed point



Building up continuum space and geometry

Goal: extract continuum geometric (gravitational) physics (dynamics) from QG (GFT) models



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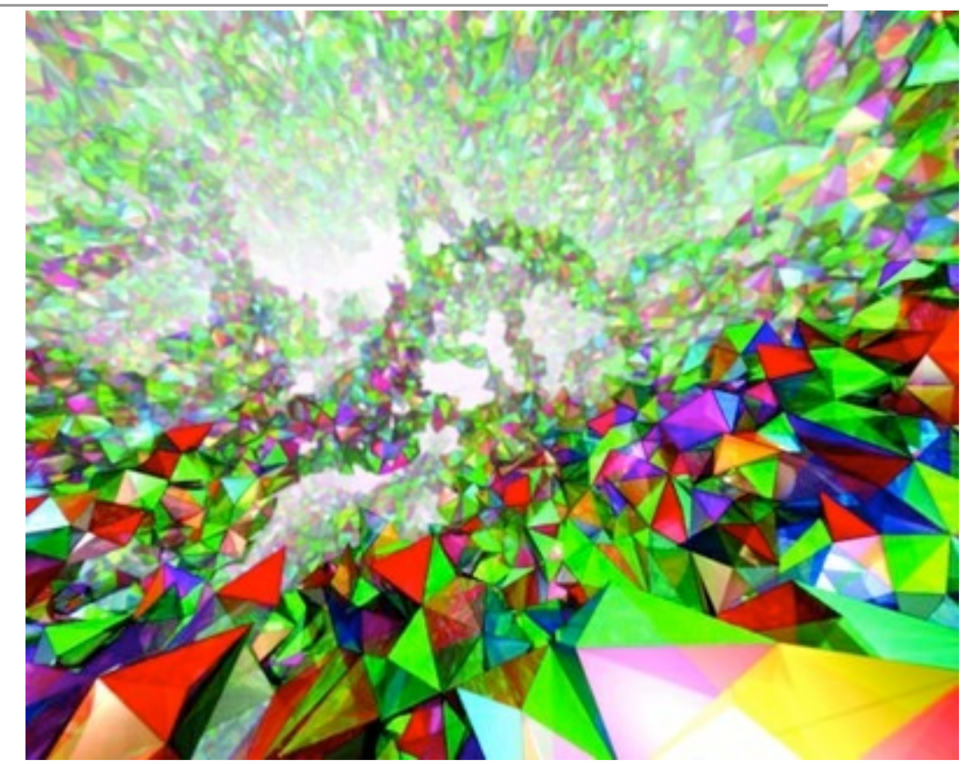

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This means:

- control QG states encoding large numbers of microscopic QG dofs
- identify those with (approximate) continuum geometric interpretation
- characterise their (geometric) properties in terms of observables
- extract their effective dynamics and recast it in GR+QFT form

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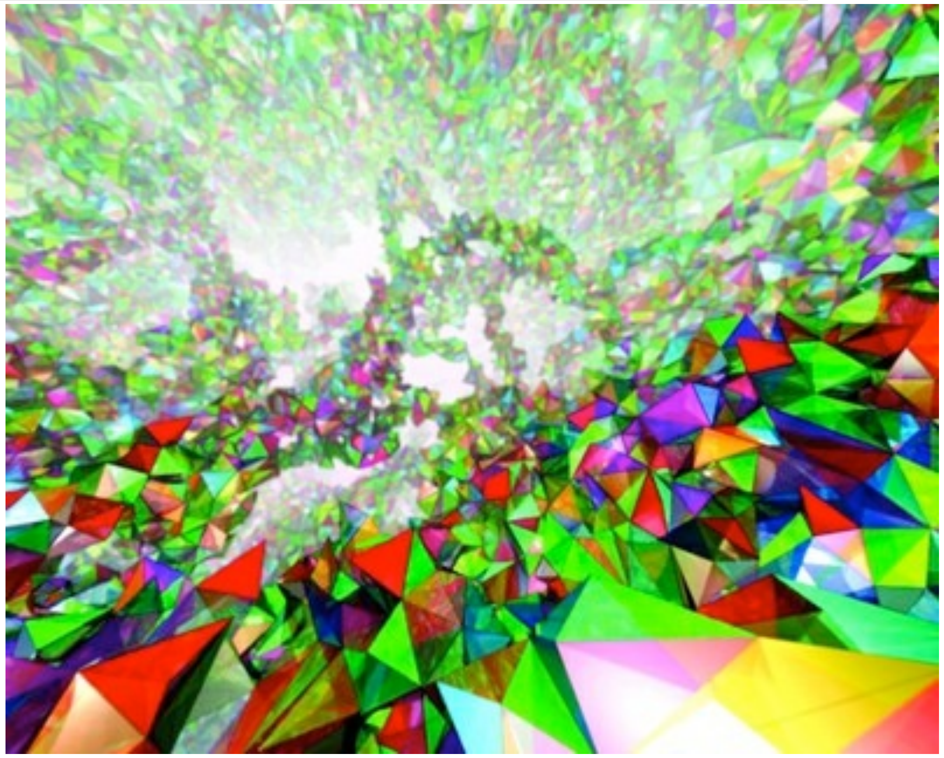

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This requires:

- controlling large graphs/complexes superpositions
- coarse graining of description
- approximations of both states, observables and dynamics

Here: take advantage of QFTformalism/methods (universe as a quantum many-body system - cosmology as QG hydrodynamics)

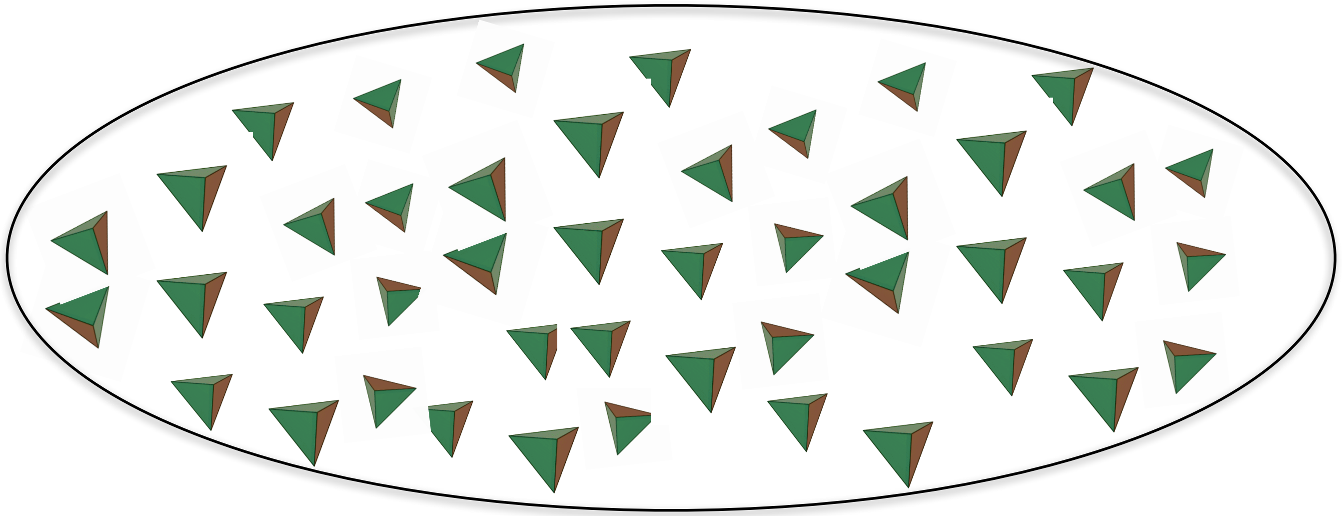
GFT condensate cosmology

Gielen, DO, Sindoni, '13; Calcagni, De Cesare, Gielen, DO, Pithis, Sakellariadou, Sindoni, Wilson-Ewing, …

Simple GFT condensates as homogeneous continuum geometries (not encoding any topological information)

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

$$\hat{\sigma} := \int d^4g\, \sigma(g_I)\hat{\varphi}^\dagger(g_I) \qquad \sigma(g_I k) = \sigma(g_I)$$



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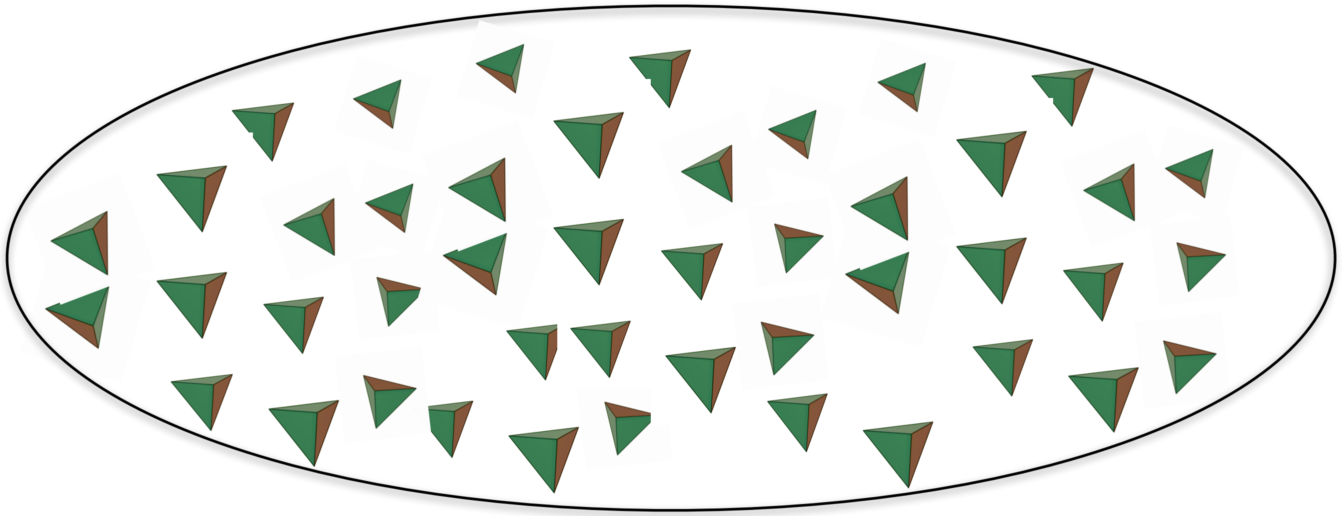

$\sigma\left(\mathcal{D}\right)$

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

$$\begin{aligned}\mathcal{D} \;&\simeq\; \{\text{geometries of tetrahedron}\} \simeq \\ &\simeq\; \{\text{continuum spatial geometries at a point}\} \simeq \\ &\simeq\; \text{minisuperspace of homogeneous geometries}\end{aligned}$$

Gielen, ‘14

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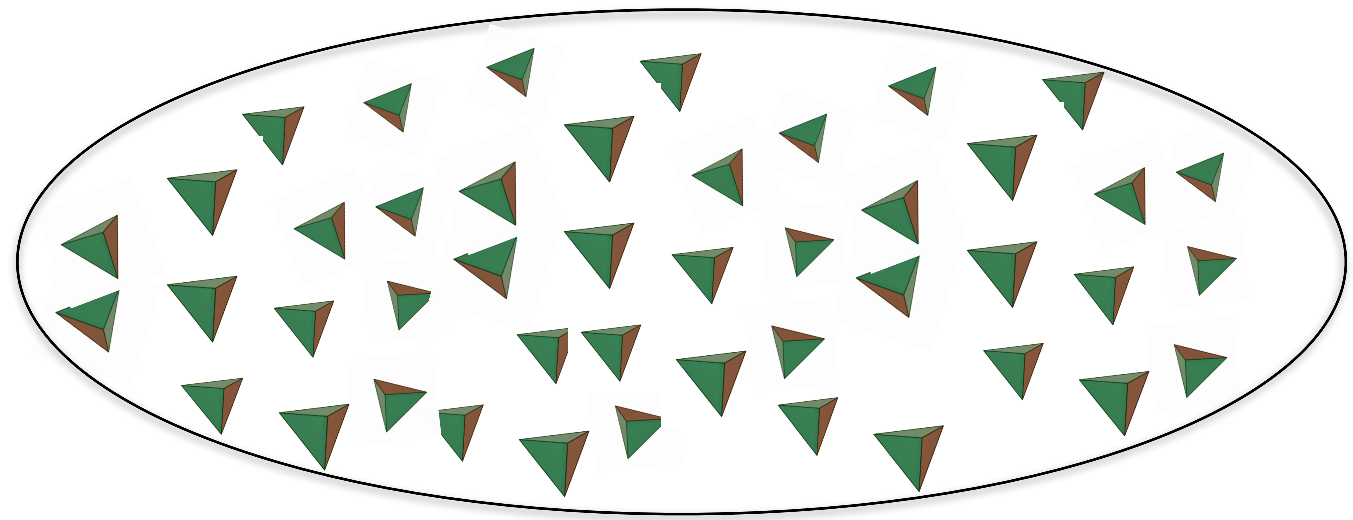

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Gielen, ‘14

Corresponding effective dynamics: GFT eqns of motion

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i.e. mean field (Gross-Pitaevskii) hydrodynamics

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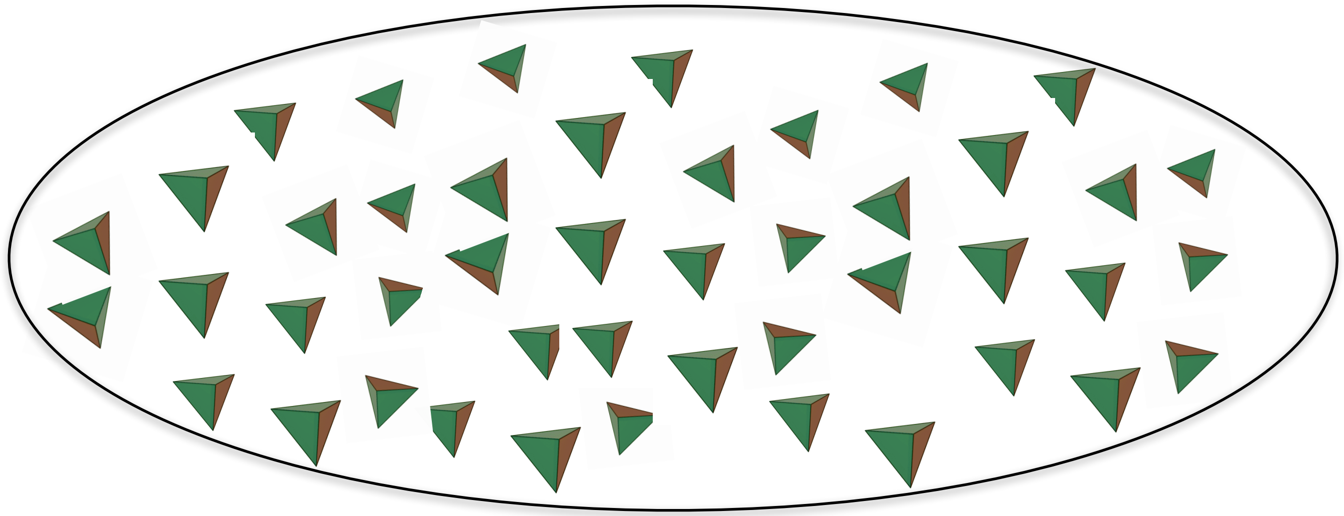

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non-linear and non-local extension of quantum cosmology-like equation for "collective wave function"

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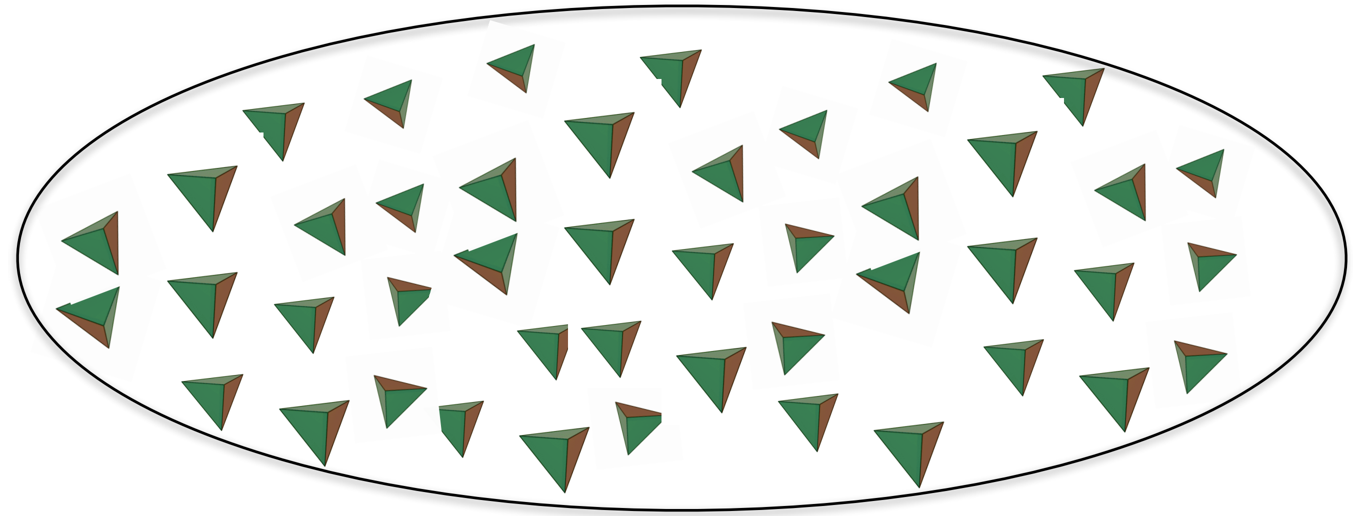

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Cosmology as QG (condensate) hydrodynamics

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DO, Sindoni, Wilson-Ewing, '16

- (generalised) EPRL model for 4d Lorentzian QG with SU(2) data, coupled to (discretised) (pre-)scalar field

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- coupling of free massless scalar field

$$\hat{\varphi}(g_v) \to \hat{\varphi}(g_v, \phi)$$

$$|\sigma\rangle \sim \exp\left(\int \mathrm{d}g_v \mathrm{d}\phi\, \sigma(g_v, \phi) \hat{\varphi}^\dagger(g_v, \phi) \right) |\mathbf{0}\rangle$$

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- effective condensate hydrodynamics (non-linear quantum cosmology):

$$\boxed{A_j \partial_\phi^2 \sigma_j(\phi) - B_j \sigma_j(\phi) + w_j \sigma_j(\phi)^4 = 0}$$

functions A, B, w define the details of the EPRL model

GFT interaction terms sub-dominant

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- key relational observables (expectation values in condensate state) with scalar field as clock:

universe volume (at fixed "time") $\quad V(\phi) = \sum_j V_j \bar{\sigma}_j(\phi) \sigma_j(\phi) = \sum_j V_j \rho_j(\phi)^2$

momentum of scalar field (at fixed "time") $\quad \pi_\phi = \langle \sigma | \hat{\pi}_\phi(\phi) | \sigma \rangle = \hbar \sum_j Q_j$

energy density of scalar field (at fixed "time") $\quad \rho = \frac{\pi_\phi^2}{2V^2} = \frac{\hbar^2 (\sum_j Q_j)^2}{2(\sum_j V_j \rho_j^2)^2}$

$V_j \sim j^{3/2} \ell_{\mathrm{Pl}}^3$

$\sigma_j(\phi) = \rho_j(\phi) e^{i\theta_j(\phi)}$

Q = constant of motion

Emergent bouncing cosmology from full QG

DO, Sindoni, Wilson-Ewing, '16

effective dynamics for volume - generalised Friedmann equations: (GFT interaction terms sub-dominant)

$$\boxed{\left(\frac{V'}{3V}\right)^2 = \left(\frac{2\sum_j V_j\,\rho_j\sqrt{E_j - \frac{Q_j^2}{\rho_j^2} + m_j^2\rho_j^2}}{3\sum_j V_j\rho_j^2}\right)^2}$$

$$\boxed{\frac{V''}{V} = \frac{2\sum_j V_j\left[E_j + 2m_j^2\rho_j^2\right]}{\sum_j V_j\rho_j^2}}$$

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E = constant of motion

classical approx. $\rho_j^2 \gg |E_j|/m_j^2$ and $\rho_j^4 \gg Q_j^2/m_j^2$

$$\left(\frac{V'}{3V}\right)^2 = \left(\frac{2\sum_j V_j\,m_j\,\rho_j^2}{3\sum_j V_j\rho_j^2}\right)^2$$

$$\frac{V''}{V} = \frac{4\sum_j V_j m_j^2\rho_j^2}{\sum_j V_j\rho_j^2}$$

approx. classical Friedmann eqns if $m_j^2 \approx 3G_N$

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E = constant of motion

classical approx. $\rho_j^2 \gg |E_j|/m_j^2$ and $\rho_j^4 \gg Q_j^2/m_j^2$

$$\rightarrow \quad \boxed{\left(\frac{V'}{3V}\right)^2 = \left(\frac{2\sum_j V_j\, m_j\, \rho_j^2}{3\sum_j V_j \rho_j^2}\right)^2} \qquad \boxed{\frac{V''}{V} = \frac{4\sum_j V_j m_j^2 \rho_j^2}{\sum_j V_j \rho_j^2}}$$

approx. classical Friedmann eqns if $m_j^2 \approx 3G_N$

$$\rightarrow \quad \exists j \;/\; \rho_j(\phi) \neq 0 \;\forall \phi \quad \rightarrow \quad \boxed{V = \sum_j V_j \rho_j^2}$$

remains positive at all times
(with single turning point)

generic quantum bounce (solving classical singularity)!

M. De Cesare, M. Sakellariadou, '16

Accelerated phase after bounce: QG inflation?

M. De Cesare, M. Sakellariadou, '16

M. De Cesare, A. Pithis, M. Sakellariadou, '16

for: $V = a^3$ we have:

$$\frac{\ddot{a}}{a} = \frac{1}{3}\left(\frac{\pi_\phi}{V}\right)^2\left[\frac{\partial_\phi^2 V}{V} - \frac{5}{3}\left(\frac{\partial_\phi V}{V}\right)^2\right]$$

existence of accelerated expansion translates in relational time as:

$$\frac{V''}{V} > \frac{5}{3}\left(\frac{V'}{V}\right)^2$$

$$\underbrace{4m^2 + \frac{2E}{\rho^2}}_{\text{positive}} > \frac{20}{3}\underbrace{g^2}_{\text{zero}}$$

near the bounce

detailed study of behaviour of solutions after bounce confirm a distinct accelerated phase

issue is: number of e-folds

$$N = \frac{2}{3}\log\left(\frac{\rho_{\text{end}}}{\rho_{\text{bounce}}}\right)$$

can we get at least N ~ 60?

does the acceleration last long enough (to solve cosmological problems)?

Accelerated phase after bounce: QG inflation?

M. De Cesare, A. Pithis, M. Sakellariadou, '16

- in effective cosmological dynamics neglecting GFT interactions:

$$0.119 \lesssim N \lesssim 0.186$$

acceleration is too short-lived to be physically useful

- including effects of GFT interactions (in phenomenological way):

$$S = \int \mathrm{d}\phi \, \left(A \, |\partial_\phi \sigma|^2 + \mathcal{V}(\sigma) \right)$$

$$\mathcal{V}(\sigma) = B|\sigma(\phi)|^2 + \frac{2}{n} w |\sigma|^n + \frac{2}{n'} w' |\sigma|^{n'}$$

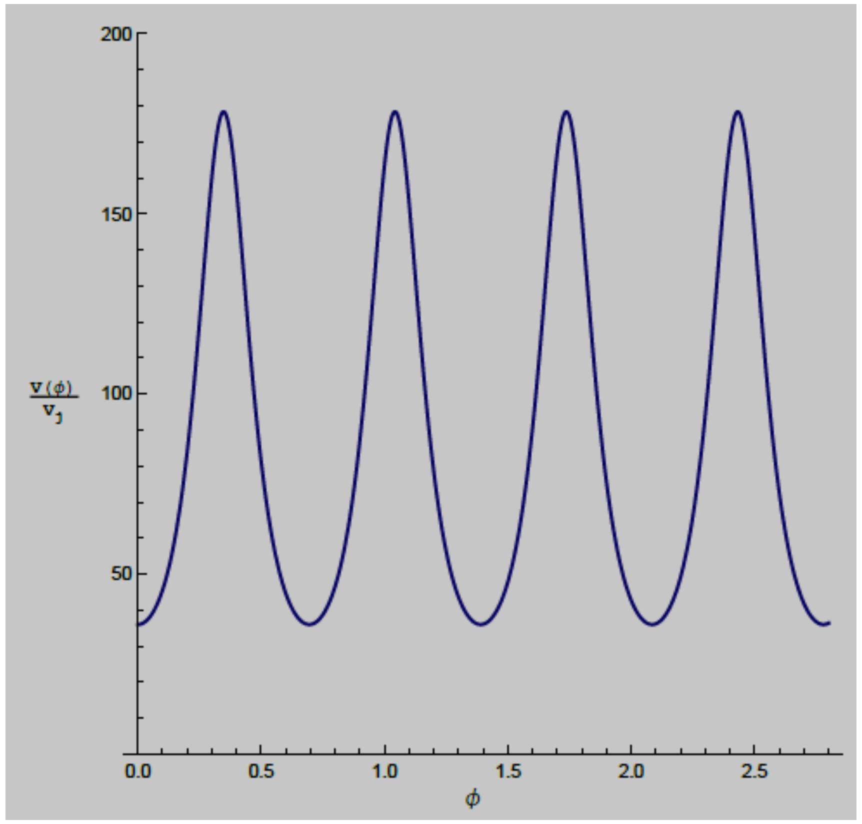
$$\sigma = \rho \, \mathrm{e}^{i\theta}$$

$$\partial_\phi^2 \rho - m^2 \rho - \frac{Q^2}{\rho^3} + \lambda \rho^{n-1} + \mu \rho^{n'-1} = 0$$

one finds:

- bounce
- accelerated expansion following bounce
- decelerated phase and recollapse

cyclic universe



moreover:

- N at least ~ 60
- no intermediate deceleration between beginning and end of accelerated phase

$\lambda < 0$ and $n \geq 5$ $(n' > n)$

QG-inflation from GFT condensates

So, what happens to the cosmological singularity?

Big Bounce? DO, L. Sindoni, E. Wilson-Ewing, ‘16 M. De Cesare, A. Pithis, M. Sakellariadou, ’16

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(as in LQC, but from the full QG theory!)

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novelty: it can be done!

exactly as one would do in a BEC….

Cosmological perturbations from full QG

S. Gielen, DO, '17

GFT for 4d gravity coupled to 4 free massless scalar fields used as clock and rods

+

isotropic reduction of geometric sector

$$\sigma(g_I, \phi^J) = \sum_{j=0}^{\infty} \sigma_j(\phi^J)\, \mathbf{D}^j(g_I)$$

GFT hydrodynamics equation for isotropic condensates (weak coupling)

$$\left(-B_j + A_j \partial^2_{\phi^0} + C_j\, \Delta_{\phi^i}\right) \sigma_j(\phi^J) = 0$$

small perturbations around homogeneous condensate universes

$$\sigma_j(\phi^J) = \sigma_j^0(\phi^0)(1 + \epsilon\, \psi_j(\phi^J))$$

volume fluctuations and cosmological power spectrum

$$\Delta V(\phi_0, k_i; \Phi_0, K_i) \equiv \langle \hat{\tilde{V}}(\phi^0, k_i) \hat{\tilde{V}}(\Phi^0, K_i) \rangle - \langle \hat{\tilde{V}}(\phi^0, k_i) \rangle \langle \hat{\tilde{V}}(\Phi^0, K_i) \rangle$$

$$= \delta(\phi^0 - \Phi^0) \sum_j V_j^2\, |\sigma_j^0(\phi^0)|^2 \left[(2\pi)^3 \delta^3(k_i + K_i) + \epsilon\left(\tilde{\psi}_j(\phi^0, k_i + K_i) + \overline{\tilde{\psi}_j}(\phi^0, -k_i - K_i)\right)\right]$$

naturally approximate scale invariance

- dominant part (computed on exactly homogeneous condensate) exactly scale invariant
- scale invariance tied to translation invariance of condensate
- deviations suppressed as universe expands and when inhomogeneities are negligible

small relative amplitude

$$\frac{\Delta V(\phi_0, k_i; \Phi_0, K_i)}{\langle \hat{V}(\phi_0) \rangle^2}$$

- dominant term ~ 1/N ~ 1/V
- perturbations further suppressed as universe expands
- if accelerated phase, further suppression of deviations from scale invariance
- QG inflation without inflation

Thank you for your attention!