Quantum Gravity:

A Brief Review of the Past, a Selective Picture of the Present, a Glimpse of the Future

Daniele Oriti

Arnold Sommerfeld Center for Theoretical Physics
Munich Center for Mathematical Philosophy
LMU-Munich, Germany, EU

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Quantum Gravity:
very much beyond the Standard Model

one thing clearly missing from Standard Model, making it intrinsically incomplete: gravity!

but incorporating gravity in the quantum framework of Standard Model is
not just like adding a new particle or a new interaction…..

….it means revising drastically our very notions of space and time,
and the very foundations of our description of the universe

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

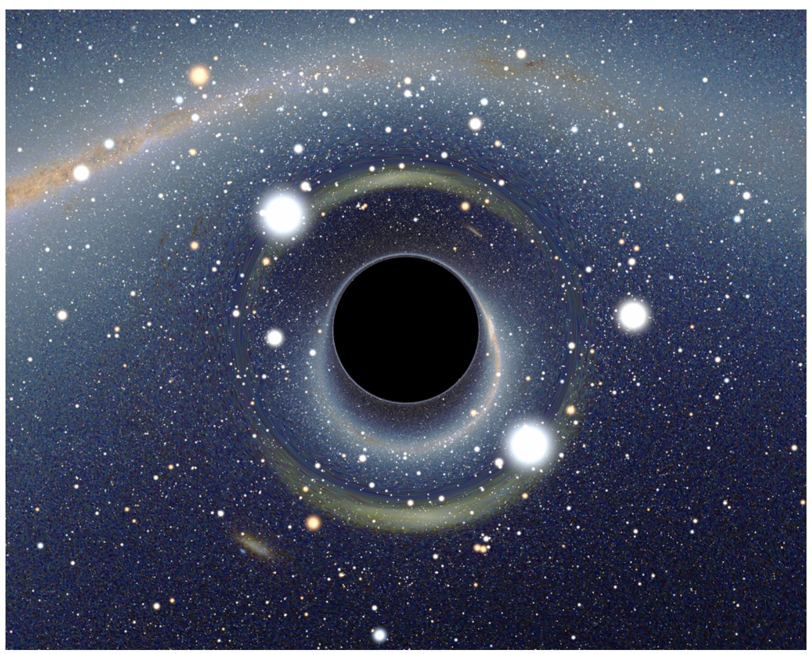
so, what are, really, space, time, geometry, and matter?

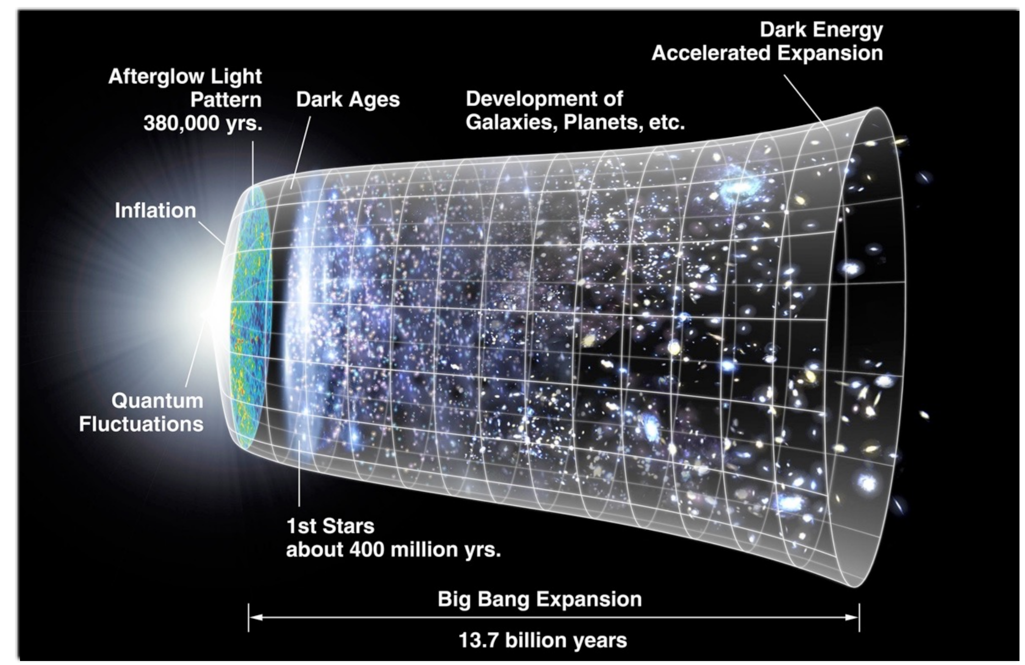
Why we need to go beyond GR and QFT

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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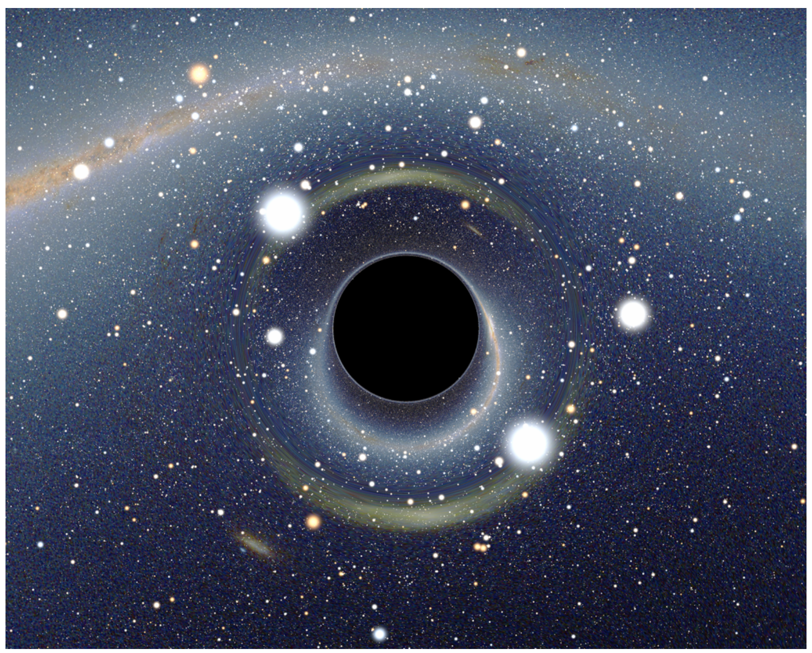

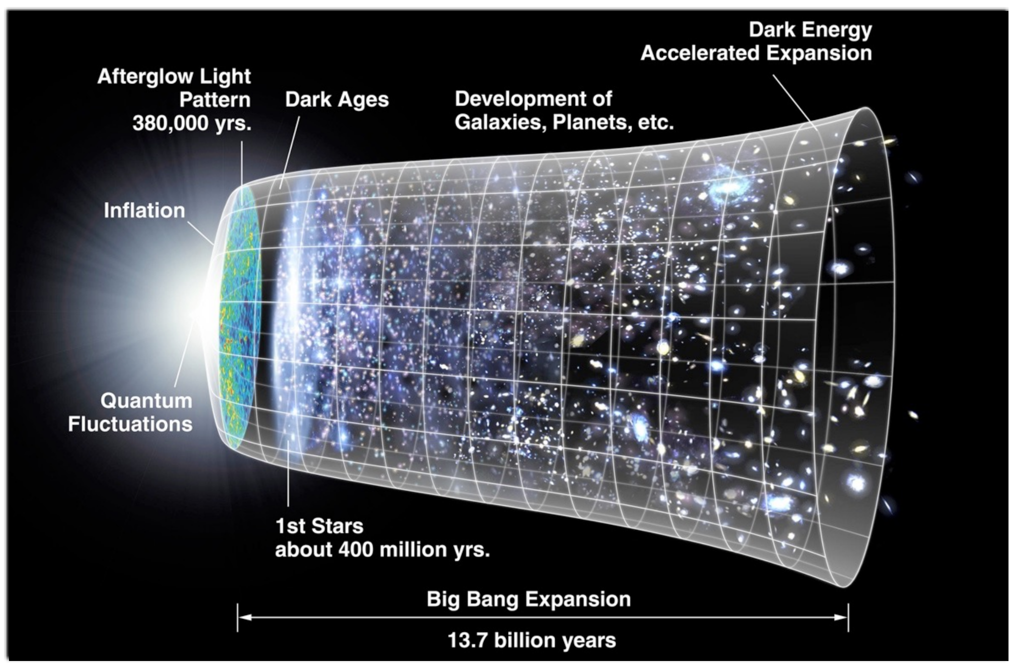

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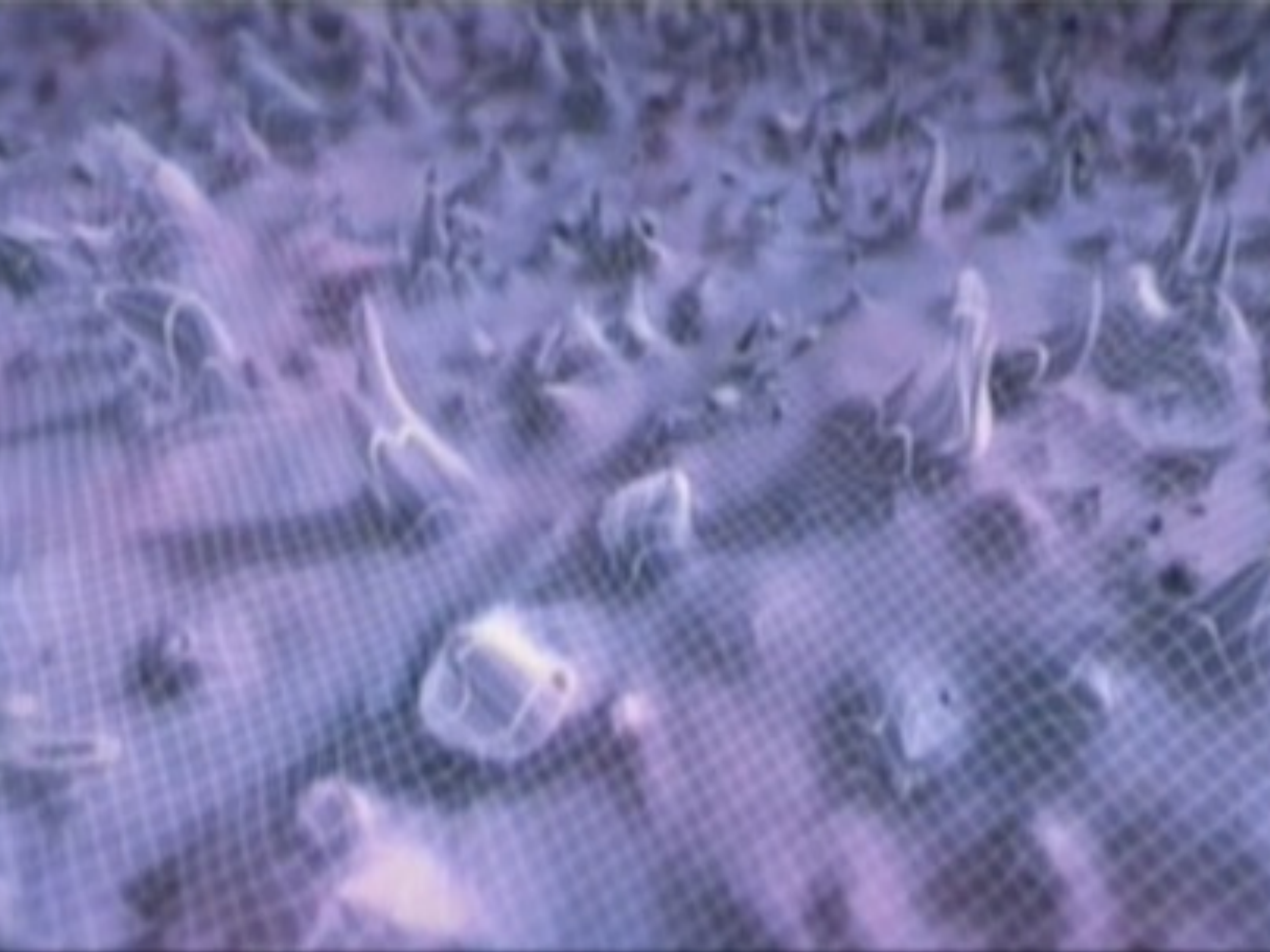
- what happens to quantum fields close to big bang? what generates cosmological fluctuations, and how?

- 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

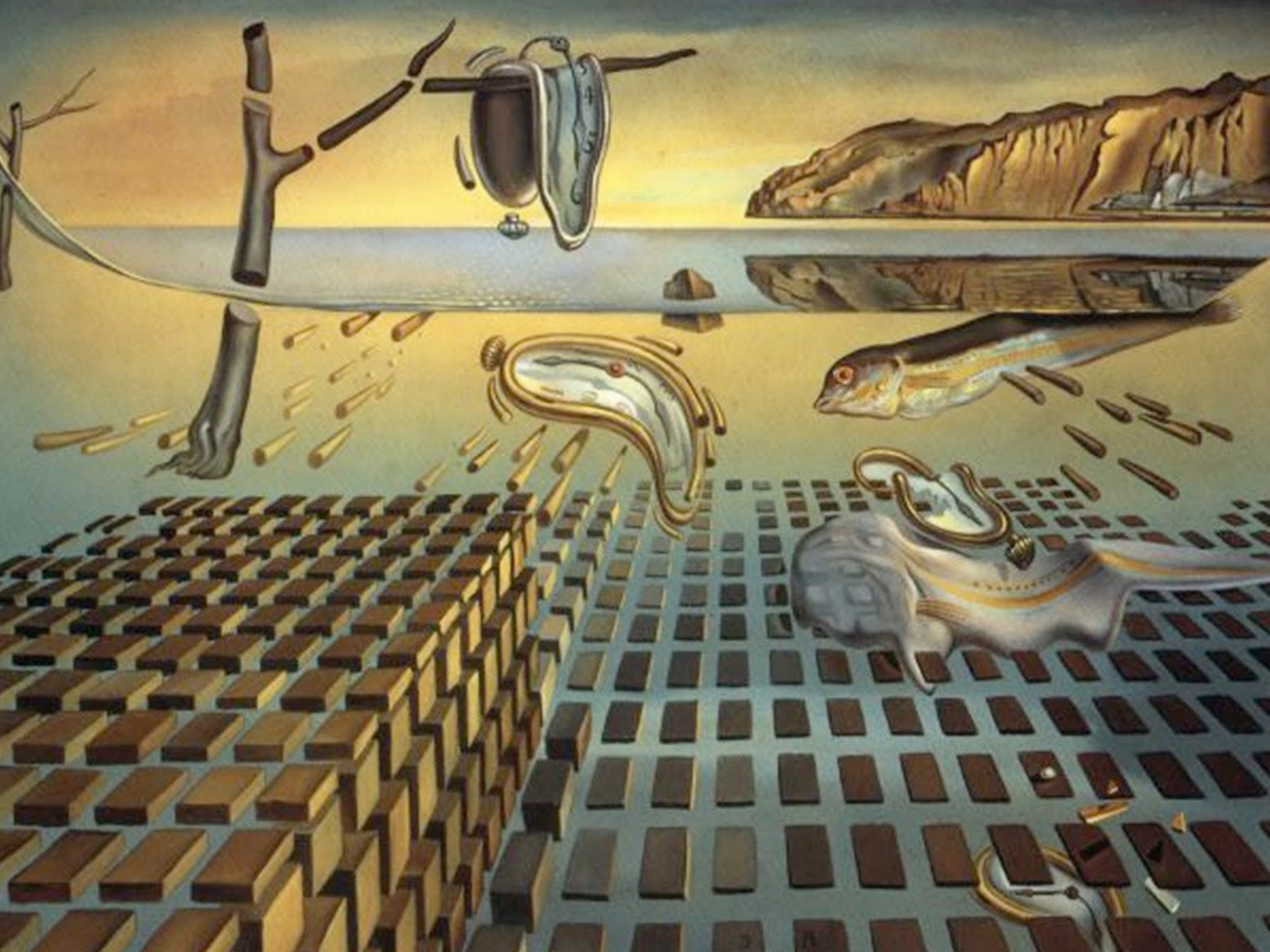
hints of disappearance of spacetime itself, more radical departure from GR and QFT

- 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")?



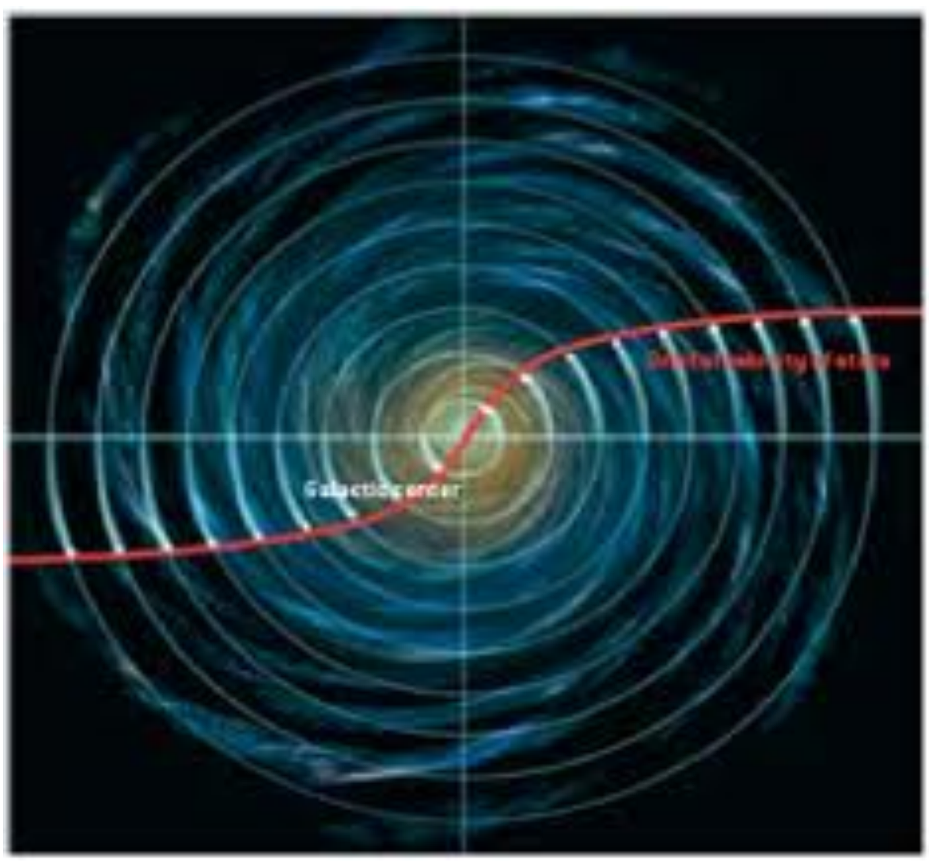
Why we need to go beyond GR and QFT

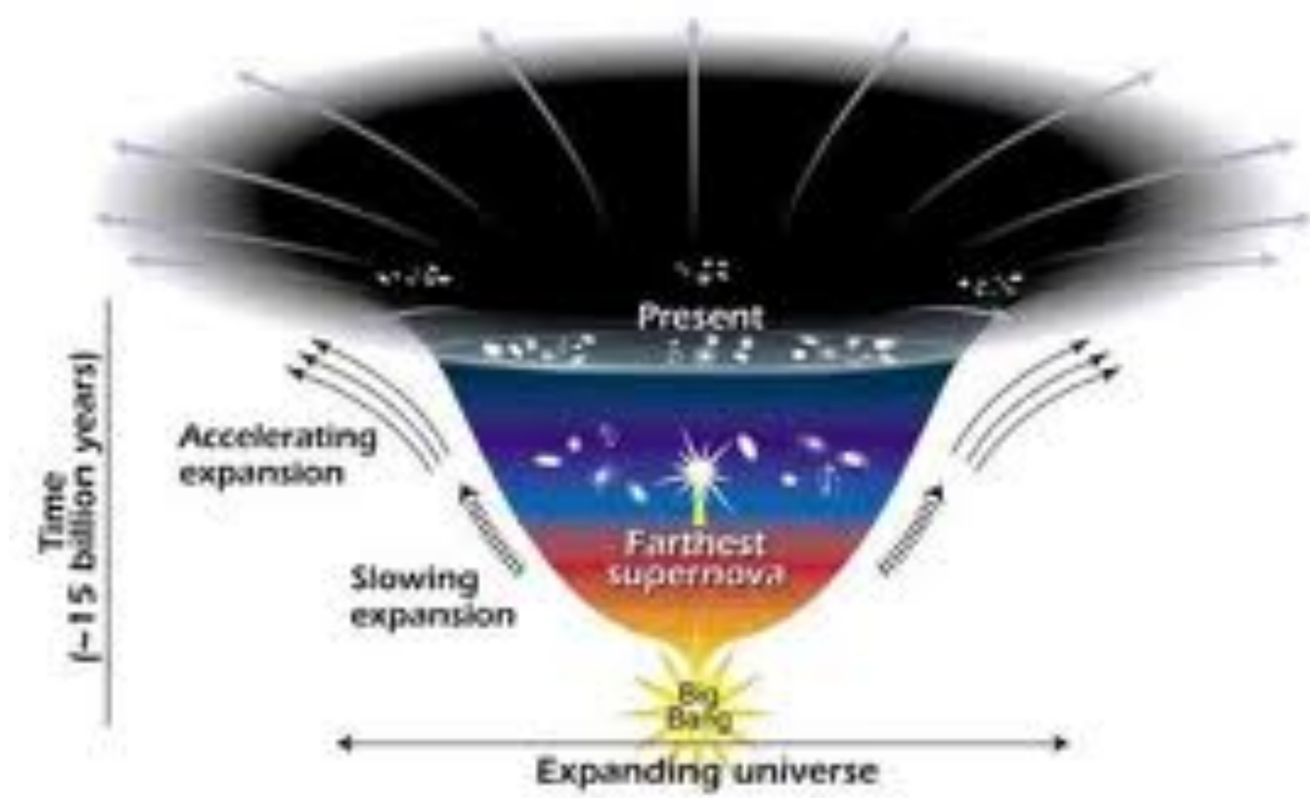
if spacetime (with its continuum structures, metric, matter fields, topology) is emergent,

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

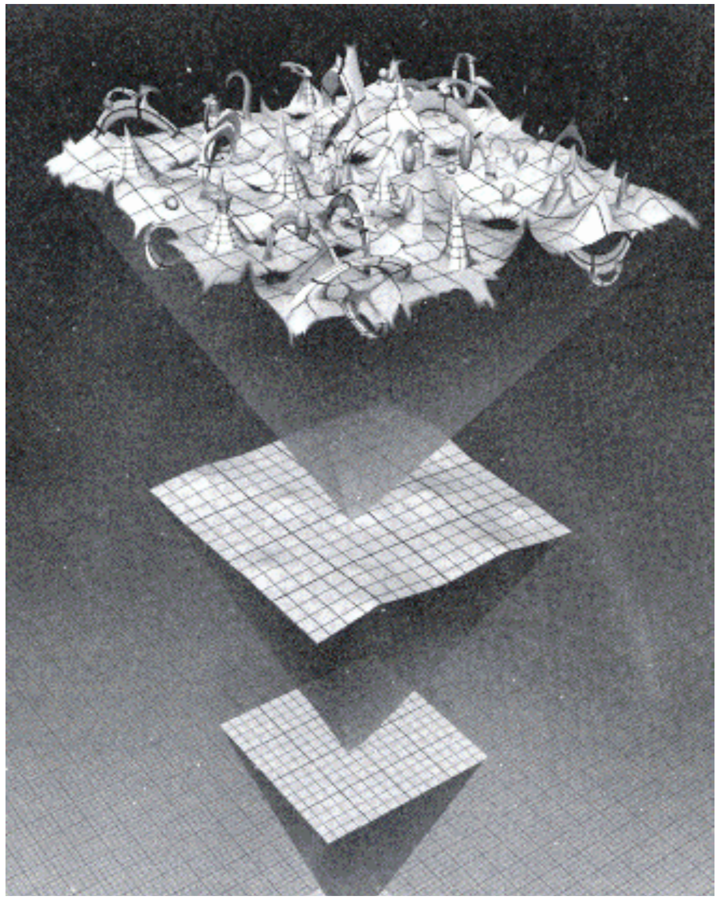
What has to change (in going from GR to QG)

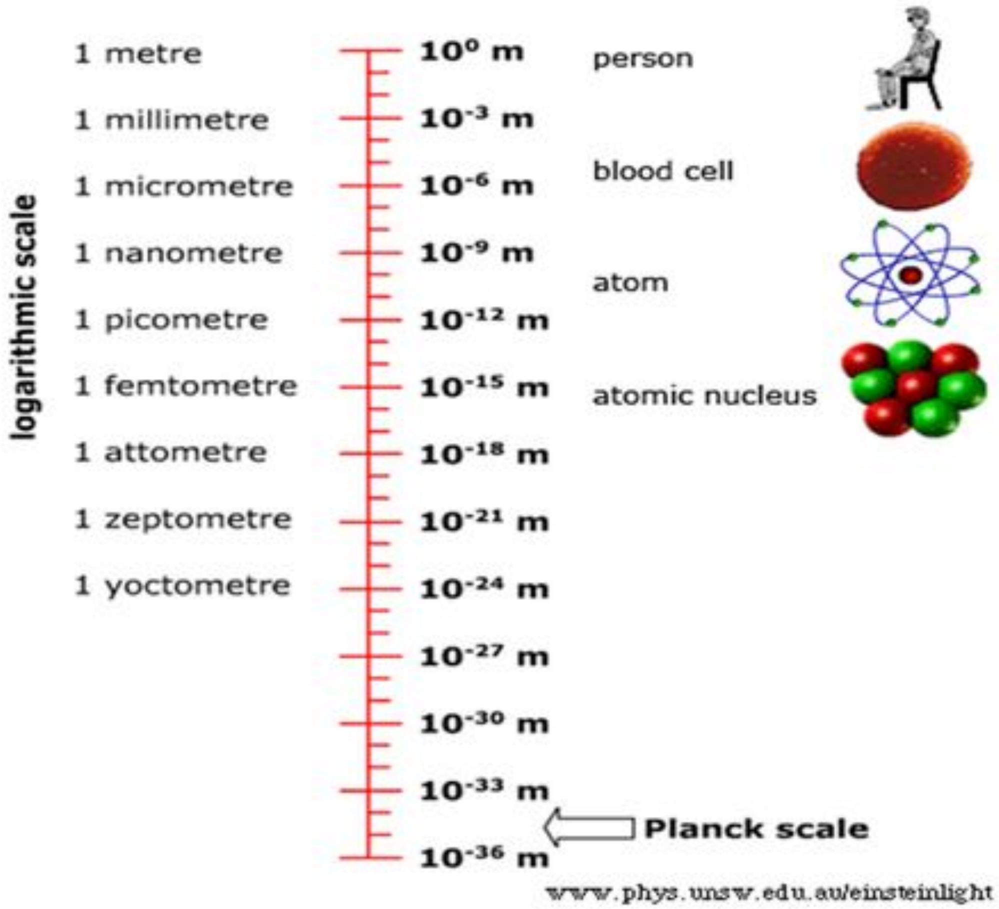
- quantum fluctuations (superpositions) of spacetime structures
  - geometry (areas, distances, volumes, curvature, etc)
  - causality (causal relations)
  - topology?
  - dimensionality?
- breakdown of continuum description of spacetime?
  - fundamental discreteness? of space? of time?
  - entirely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

no spacetime or geometry?

how can we even talk of “scales”?

total failure of effective field theory intuition?





Quantum Gravity: what happened so far

(years between 1950-2005)

General strategy being followed:

quantise GR, adapting and employing standard techniques

different research directions are born, corresponding to different quantization techniques:

perturbative quantization, canonical quantization, covariant (path integral) quantization

all achieve key insights

all get stuck and die of starvation (or are maintained alive in a vegetative state)

Quantum Gravity: (covariant) perturbative quantization

DeWitt (1950), Gupta (1952): general formulation of perturbative quantization

metric perturbations

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

flat metric (Minkowski)

background metric provides notion of space, time and causality

linear diffeomorphisms are gauge symmetry (background breaks full symmetry)

metric perturbations are quantized analogously to other gauge interactions

“gravitons”: massless, spin-2 quanta of perturbative gravitational field

Feynman, DeWitt,… (1962-1967, …): tree-level scattering amplitudes, 1-loop corrections to. Newton’s law, background-field method, unitarity, gauge-fixing, ghosts, ….

’t Hooft,Veltman, …., Goroff, Sagnotti (1971-1986): divergences, non-rinormalizability without and with matter

proposed possible solutions:

a) add new physical ingredients (new matter, new symmetry), b) modify gravitational dynamics,
c) quantise non-perturbatively

Quantum Gravity: canonical quantization

Bergmann, Dirac (1950-1959): canonical quantization of (constrained) gauge systems

Arnowit, Deser, Misner (1961): Hamiltonian formulation of General Relativity, diffeomorphism constraints

Bergmann-Komar, Peres, DeWitt, Wheeler (1962-1967): canonical quantum gravity in ADM variables

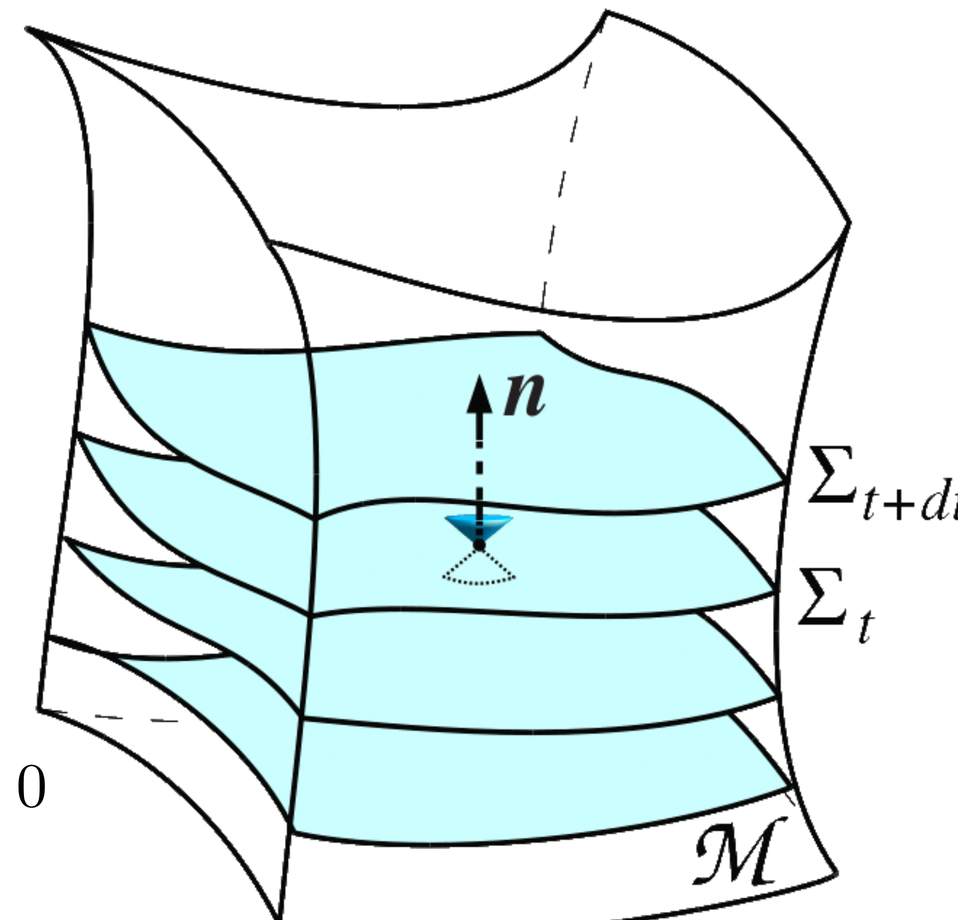
$$\{h_{ij}(x), K^{kl}(x')\} \propto \delta_{ik}\delta_{jl}\delta(x-x')$$

spatial 3-metric — extrinsic curvature

$$H_i(h_{ij}, K_{kl}) = 0$$
$$H(h_{ij}, K_{kl}) = 0$$

invariance under spatial and temporal diffeomorphisms

(encode whole dynamics)



quantum level:

$\Psi(h_{ij}) \in \mathcal{H}$

$$\widehat{H_i}\left(h_{ij}, \frac{\delta}{\delta h_{kl}}\right)\Psi(h_{ij}) = 0 \qquad \widehat{H}\left(h_{ij}, \frac{\delta}{\delta h_{kl}}\right)\Psi(h_{ij}) = 0$$

Wheeler, DeWitt, Teitelboim, Kuchar, Isham…. (1967-1987, …): properties of “superspace of 3-geometries”, problem of time, scalar product on quantum states, quantum cosmology, lots of semiclassical analyses, ….
formalism too ill-defined at mathematical level to constitute solid approach to QG (beyond semi-classical or “in-principle” analyses)

Quantum Gravity: covariant path integral quantization

Misner, Wheeler,… (1957-): idea of sum-over-histories formulation of QG, non-perturbative transition amplitudes (and scalar product) between QG states via sum over spacetime geometries

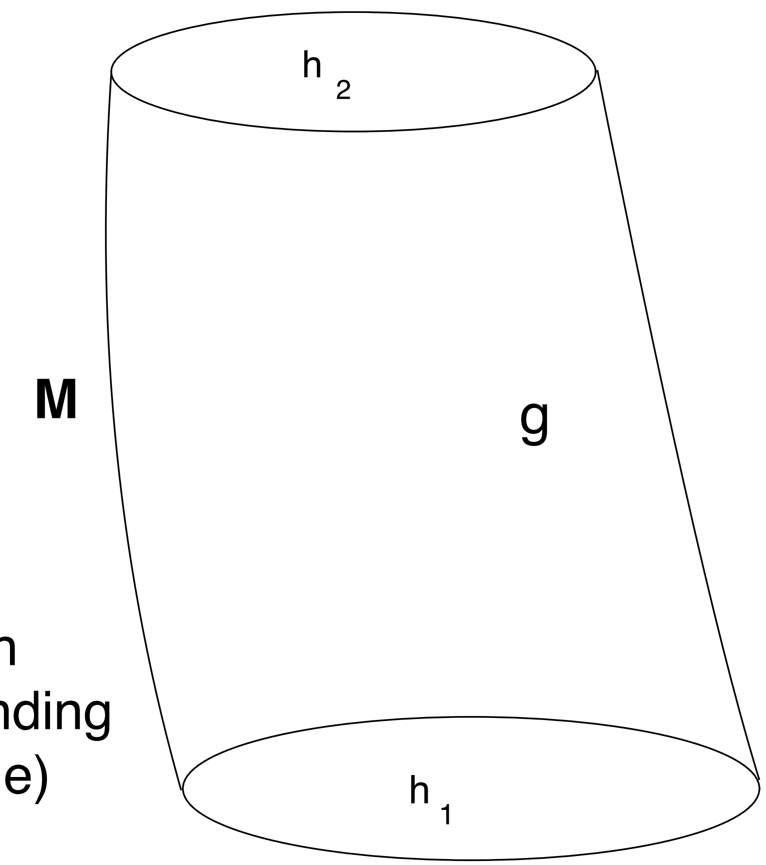
Wheeler (1963) suggests to define it via discrete lattice (Regge) regularization —-> quantum Regge calculus

transition amplitude (or scalar product) from one 3-geometry to another

$$\langle h_1 | h_2 \rangle = \int_{h_1, h_2} \mathcal{D}g \; e^{i\, S_{\mathcal{M}}(g)}$$

sum over spacetime 4-geometries

probability amplitude for each "history" (4-geometry), depending on GR action (or modified one)



Hawking, Hartle, Teitelboim, Halliwell,… (1978-1991, …): Euclidean continuation, covariant (no-boundary) definition of "wave function of the universe", relation to canonical theory, implementation of diffeomorphism symmetry, covariant quantum cosmology, lots of semi-classical applications, …….. formalism too ill-defined at mathematical level to constitute solid approach to QG (beyond semi-classical or "in-principle" analyses)

many results also within quantum Regge calculus (Rocek, Sorkin, Williams, Hamber, ….)

main lessons

a) 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)

it has to be somehow reproduced from more fundamental theory, which should also explain its failure

b) we have template (general quantum structure, implementation of symmetries, non-perturbative (phase) transitions between geometries, etc) of full non-perturbative theory in the continuum, which should be realised concretely by more fundamental theory, to the extent in which continuum picture holds

we have well-defined list of conceptual issues (concerning time, space, causality, semi-classical limit, interpretation of quantum mechanics, etc) that need to be addressed. for understanding and use of full QG

we have several suggestions of QG corrections to classical phenomena (also non-perturbative)

c) we have learned how hard is the Quantum Gravity problem, mathematically, physically, conceptually

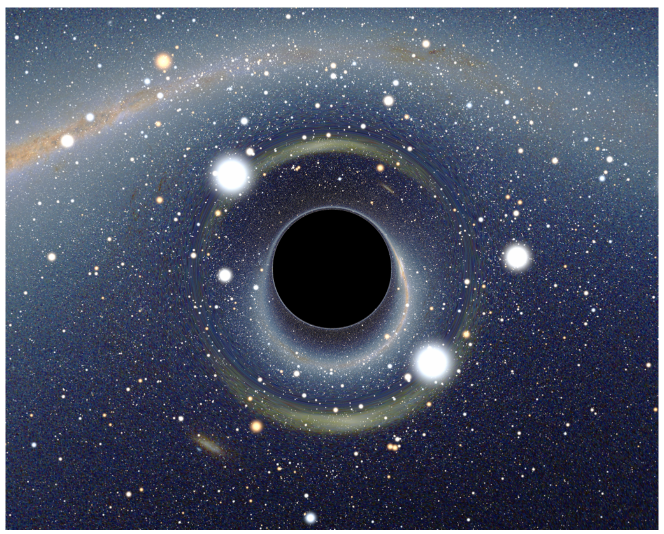
Other new things we learned (from semi-classical gravity) that are here to stay (for QG)

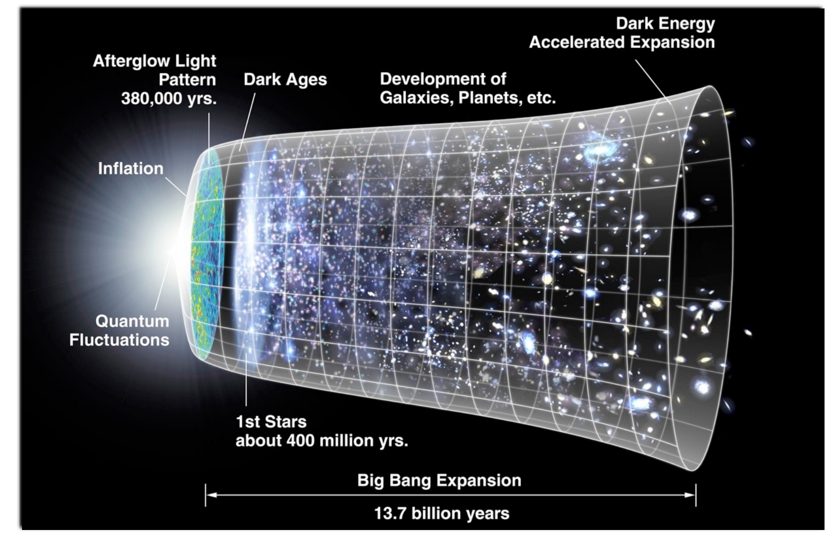
Spacetime singularities

Hawking, Penrose, Geroch, …..

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

center of black holes, big bang - quantum effects expected to be important





Black hole thermodynamics

Bekenstein, Bardeen, Carter, Hawking (1973): a notion of entropy can be formally associated to black holes, and laws of black hole mechanics recast in the form of black hole thermodynamics

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

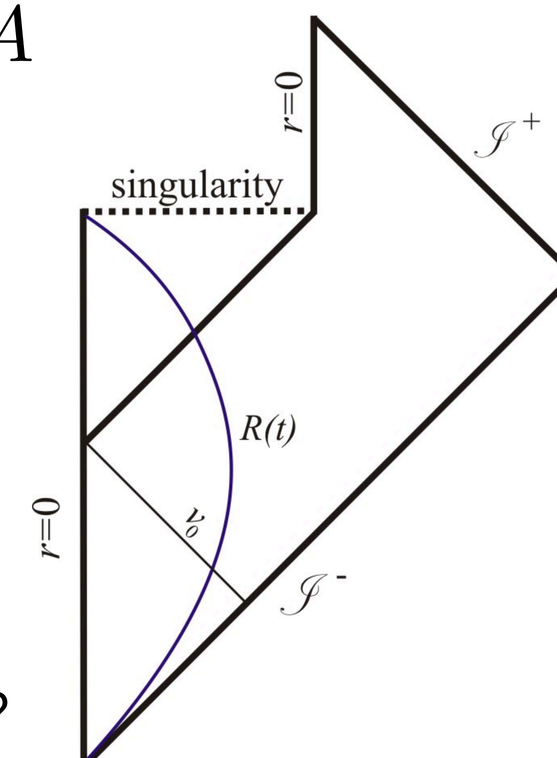
why finite? why holographic?
if of Boltzmann type, → due to which microstructure?

Hawking (1974): black holes emit thermal radiation, with temperature proportional to horizon curvature

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

↓

BHs evaporate away …. to become what? what happens to information content? → signals violation of some basic principle of spacetime physics (unitarity? locality?)



Other new things we learned that are here to stay (for QG)

spacetime thermodynamics

BH thermodynamics generalised to cosmological horizons, similar for surfaces in flat space (Unruh effect)

is any (region of) spacetime a thermodynamic. system?

Einstein's equations as equation of state

T. Jacobson (1995), ….., 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** $G(g) \propto T(\varphi, g)$

crucial: "holographic" behaviour

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

analogue gravity in condensed matter systems

C. Barcelo, S. Liberati, M. Visser, '05

effective curved metric (from background fluid) and quantum matter fields (describing excitations over fluid) from non-geometric atomic theory (quantum liquids, optical systems, ordinary fluids, …)

Unruh, Parentani, Visser, Weinfurtner, Jacobson, … (1981-…)

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

While straightforward approaches loose momentum, and new insights come from other corners of (semi-classical) gravitational physics …..

…. new QG approaches are developed, gain traction, achieve results, offer further insights

- some are (or at least start as) continuations of previous attempts in different form
- sometimes the new ingredients/hypothesis have radical, unexpected consequences
- similar mathematical structures end up being shared by several formalisms
- stages of development, languages, but also priors and goals of different approaches vary greatly

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several sub-communities form, with sometimes difficult relationships

String theory (and related)

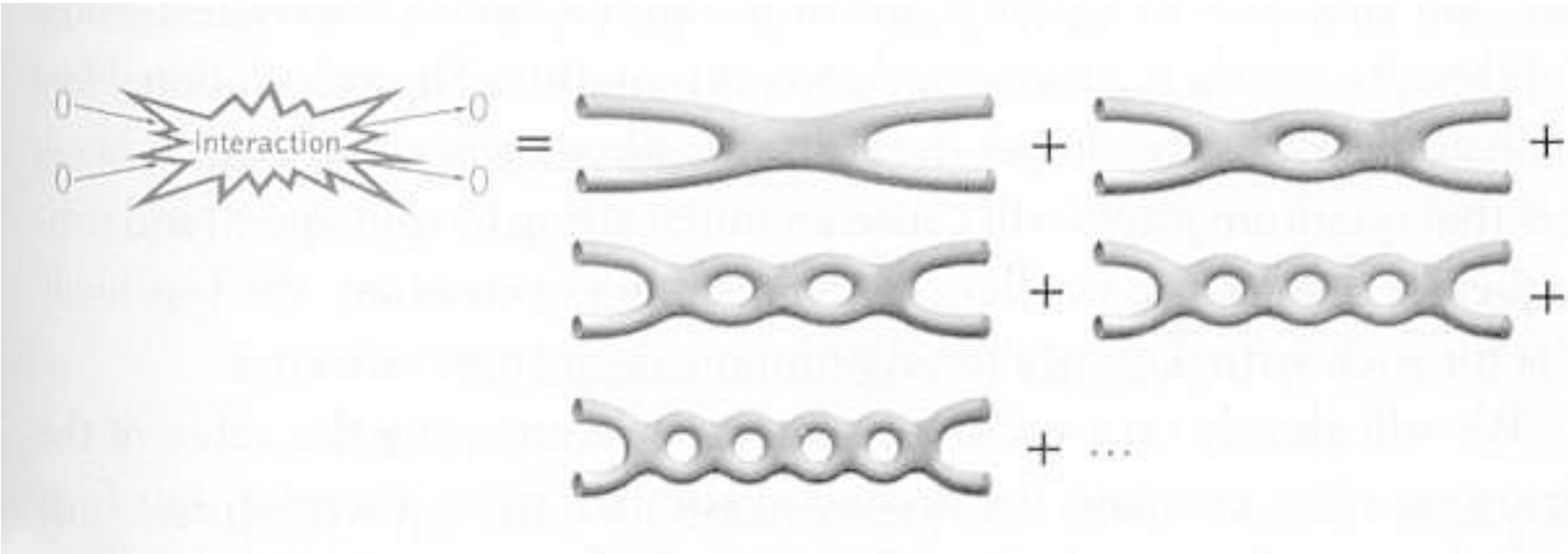
(…… , a lot of people, …..)

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

string excitations: infinite particles of any spin/mass; incl. graviton

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

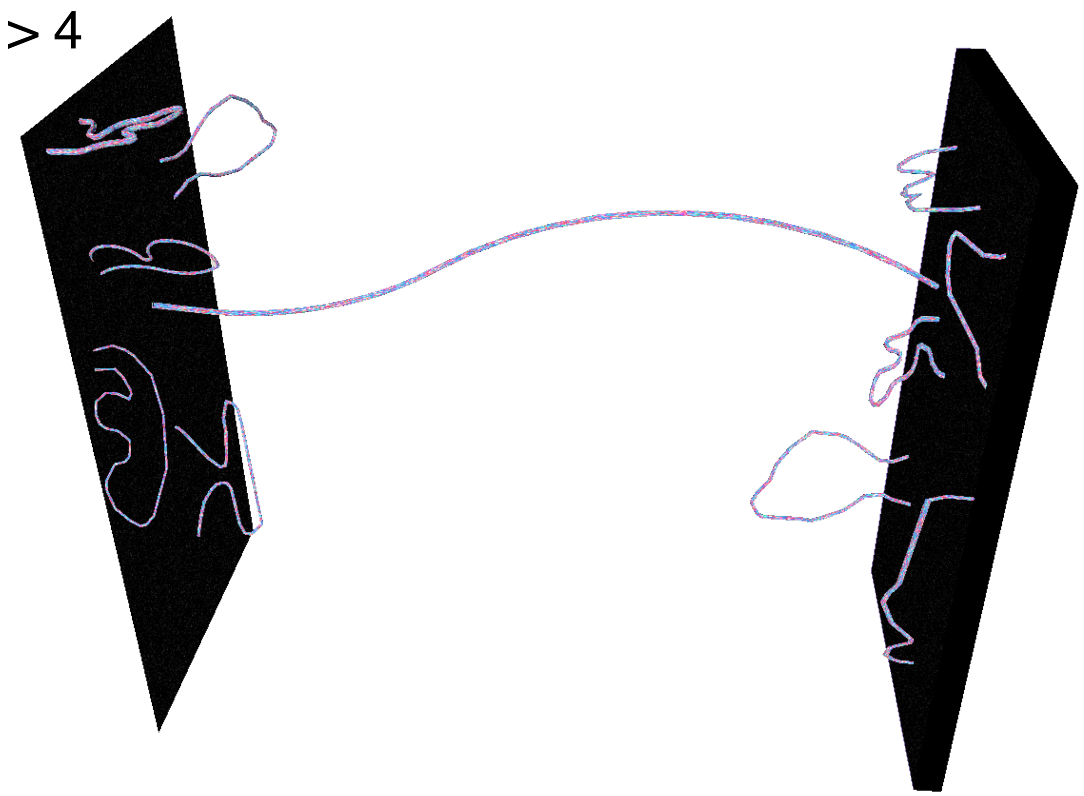
background spacetime satisfies GR equations



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

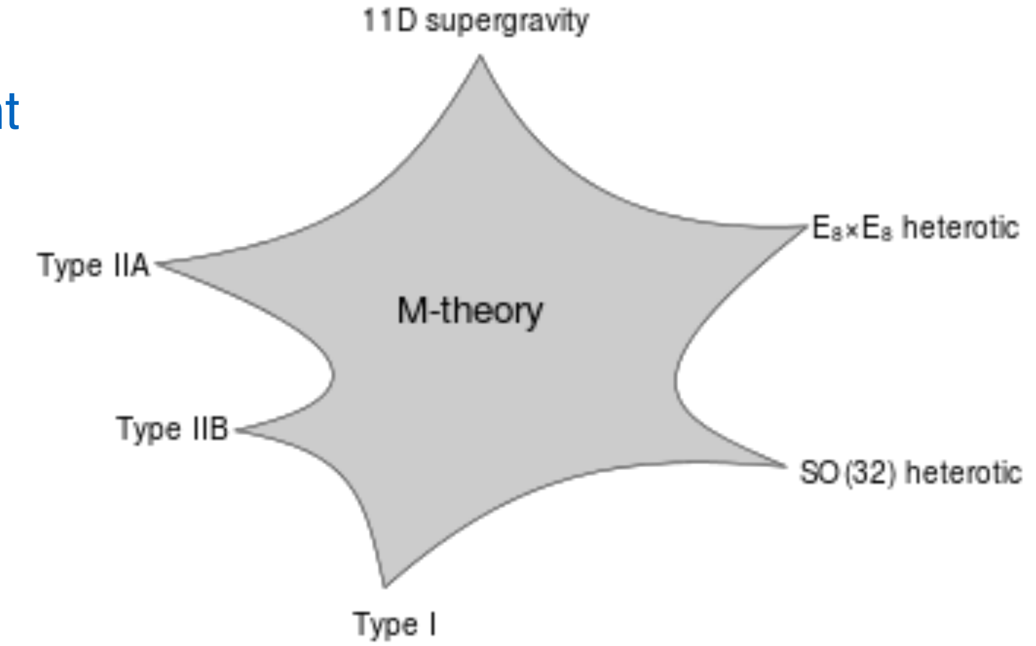
many non-perturbative aspects; extended (d>1) configurations (branes) as fundamental as strings, and interacting with them (Polchinski, …., 1994 -)



String theory (and related)

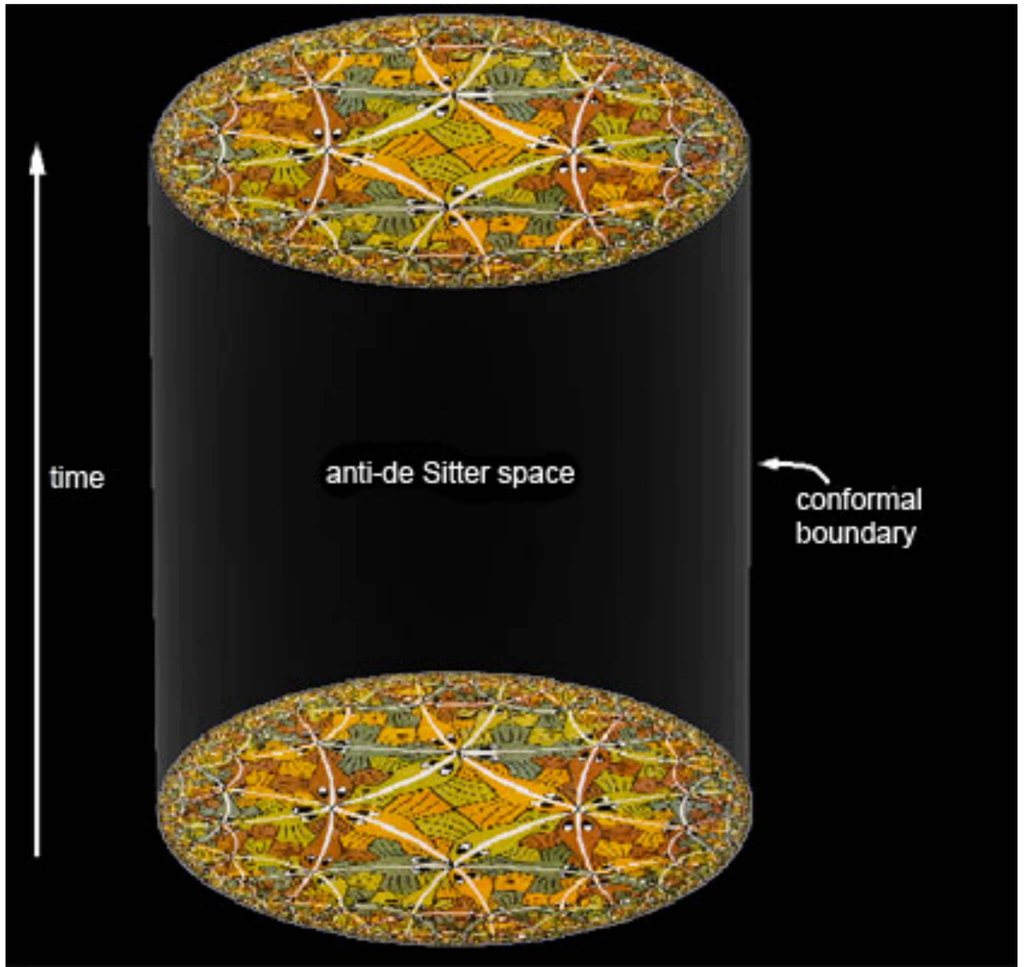
(...... , a lot of people, ...)

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

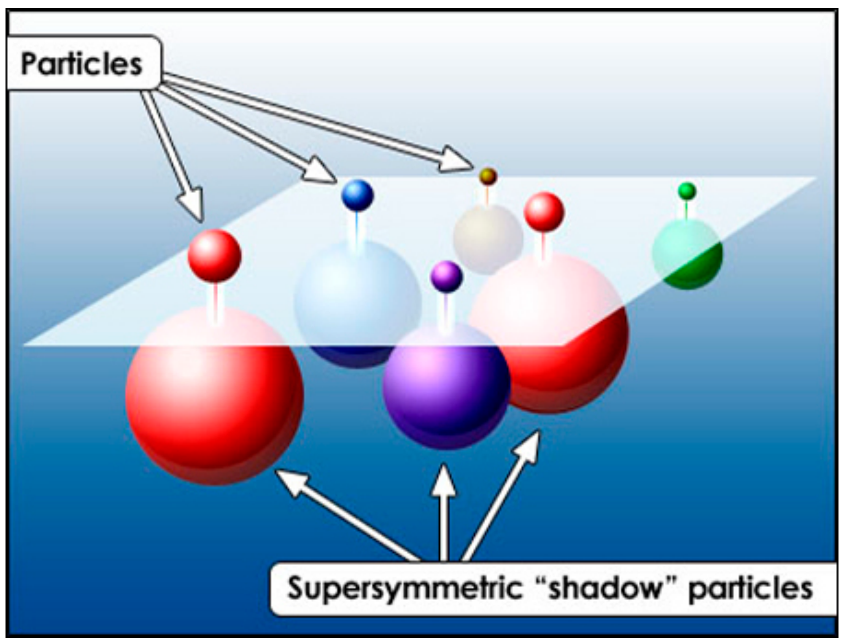
QG as QFT - Supergravity

Freedman, Ferrara, van Nieuwenheuzen, Zumino, Julia, Wess, DeWitt, Nicolai, deWit, … (1976 -)

one way out of non-renormalizability of perturbative gravity: new symmetry: supersymmetry

motivated also by extensions of Standard Model of particle physics (for any interaction a new matter field)

SUGRA is supersymmetric extension of GR with supersymmetric group replacing the local Lorentz group



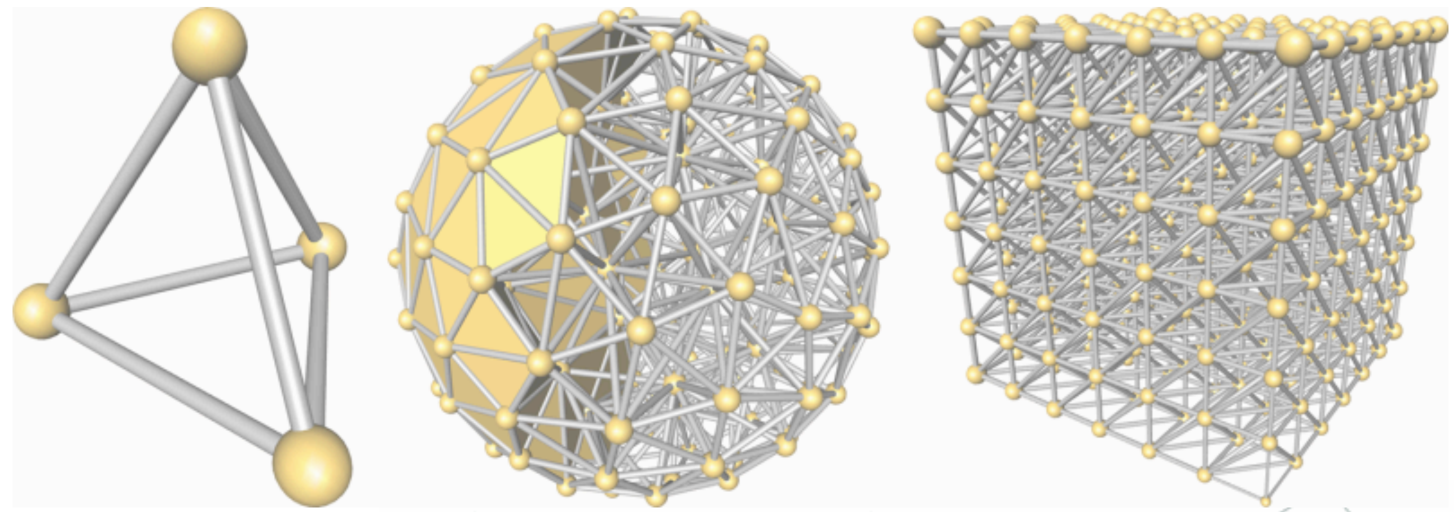
"gravitino" is super partner of "graviton")

as QFT, SUGRA is better defined, perturbatively, that are gravity ….. recently, more evidence of nice cancellation of divergences …. a perturbativela well-defined field theory of QG?

in 11 spacetime dimensions it emerges as low energy limit of string theory

QG as QFT - Lattice Quantum Gravity

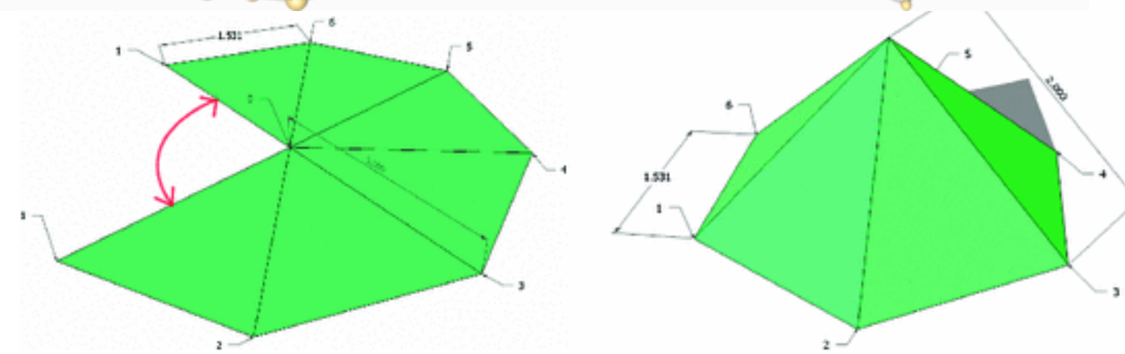
Basic idea: covariant quantisation of gravity as sum over “discrete geometries”



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

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

evidence of nice geometric (deSitter-like) continuum phase

QG as QFT - Asymptotic Safety Scenario

Quantum gravity is perturbatively non-renormalizable as QFT of the metric $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

Can it make sense non-perturbatively?

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

Effective action
(~ covariant path integral)

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

defined 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

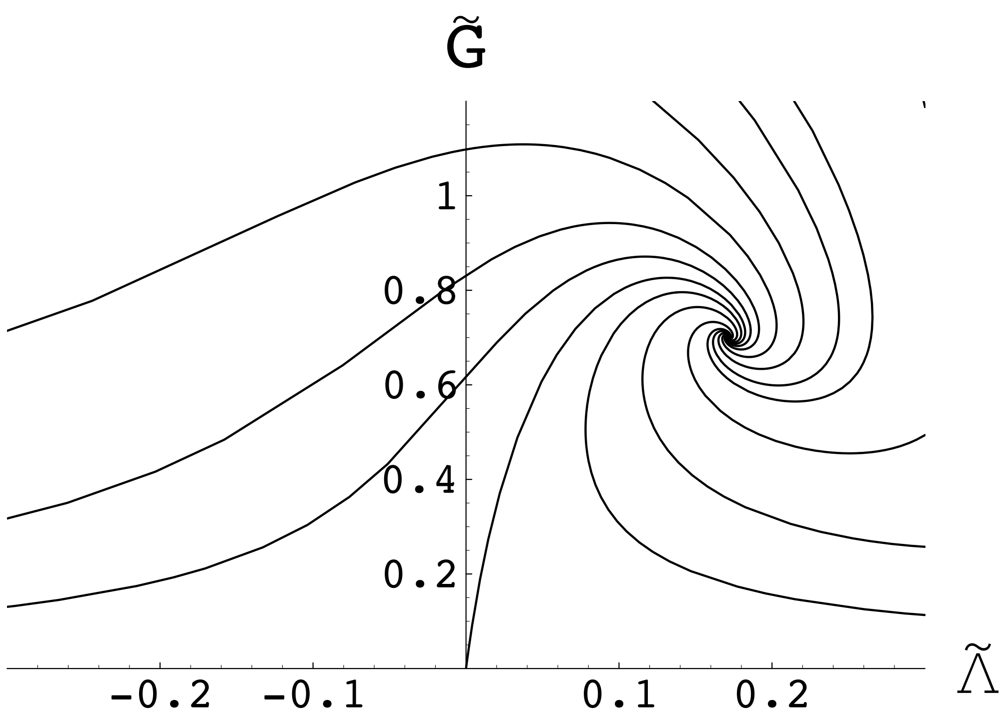
if theory has non-trivial UV fixed point then it is "asymptotically safe" and could be fundamental

necessarily studied in various truncations (+ matter fields etc)

eg Einstein-Hilbert truncation

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

accumulating evidence for existence of UV fixed point of R^2 type



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):

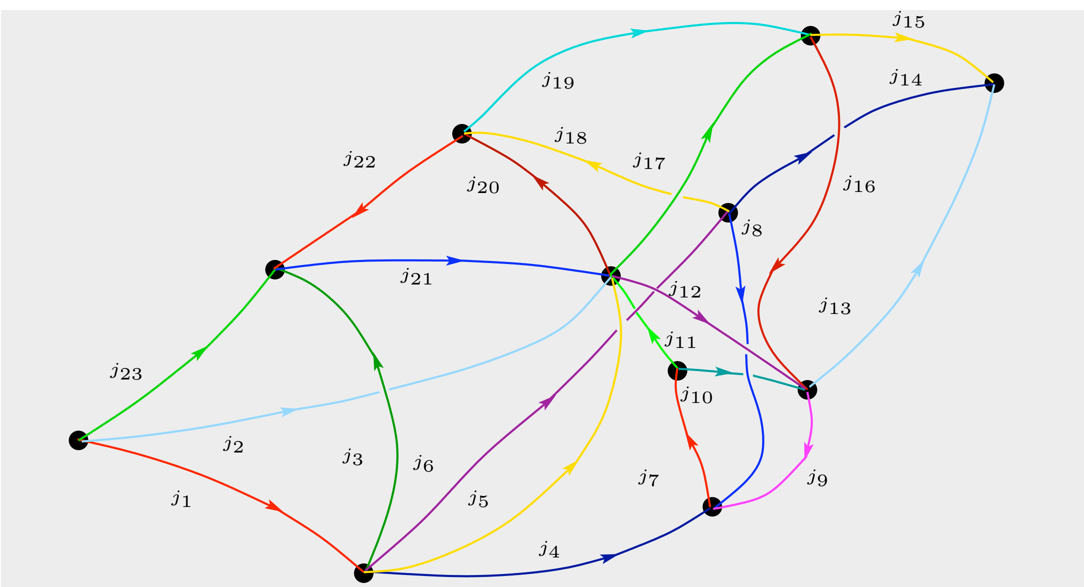
$$(A_a^i \quad , \quad E_i^b = \frac{1}{\gamma}\sqrt{e}\, e_i^b)$$

focus on gravity, matter coupled but not central

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

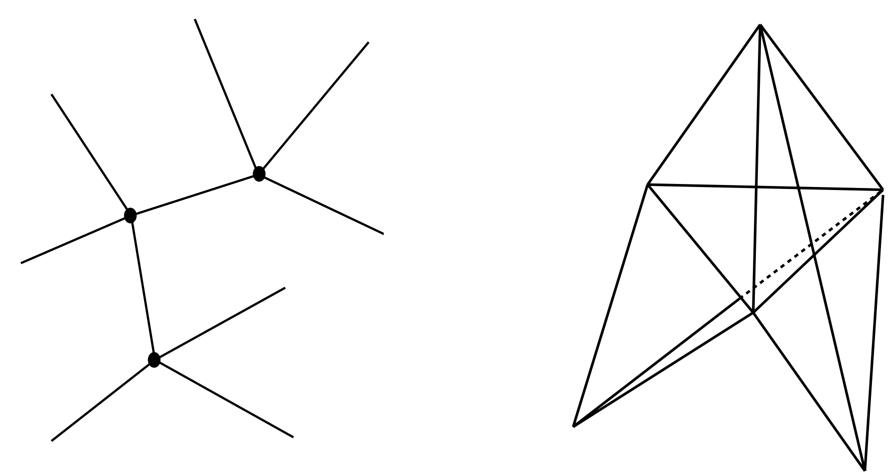
kinematical Hilbert space of quantum states: $\mathcal{H} = \lim_{\gamma} \frac{\bigcup_\gamma \mathcal{H}_\gamma}{\approx} = L^2\left(\bar{\mathcal{A}}\right)$

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



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)

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

rigorous implementation of spatial diffeomorphism invariance

loop quantum cosmology: singularity resolution

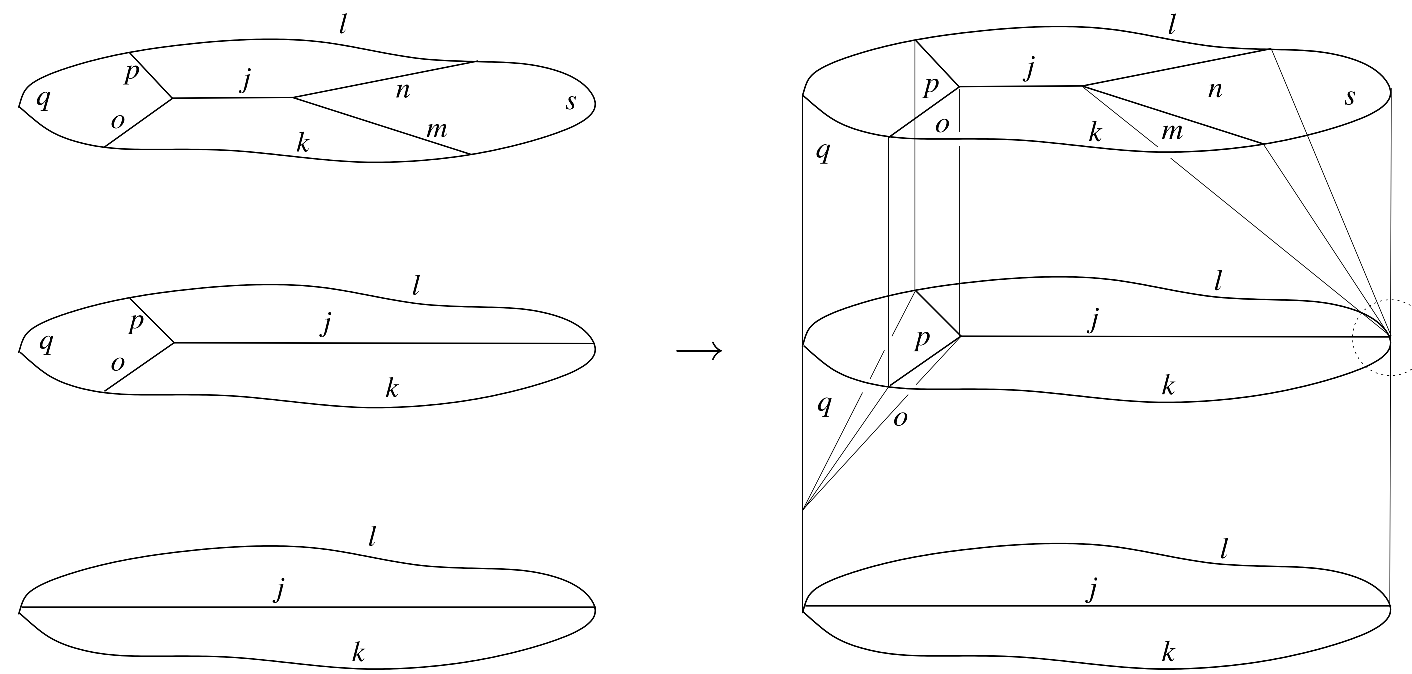
consistent implementation of Hamiltonian constraint; some solutions of it; on-shell anomaly-free algebra

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

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

correct discrete semi-classical limit in terms of Regge calculus

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

Matrix models (Migdal, Kazakov, David, Duplantier, Ambjorn, Kawai, Di Francesco, Zuber, Brezin, ...)

- discrete 2d GR on each 2d triangulation

used to define world sheet theory of strings

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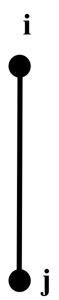

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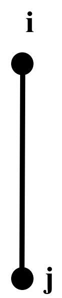

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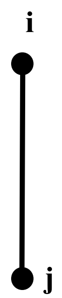

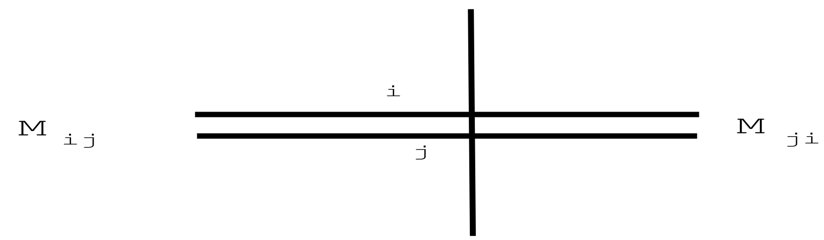

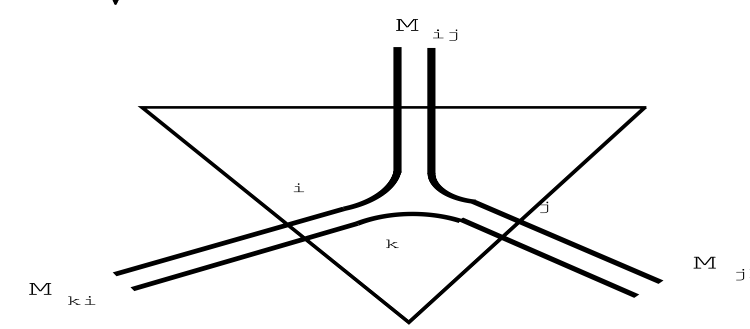

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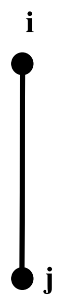

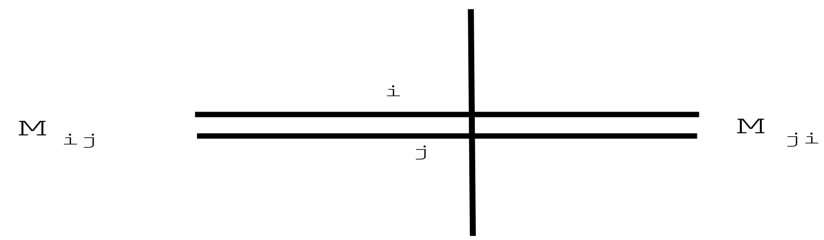

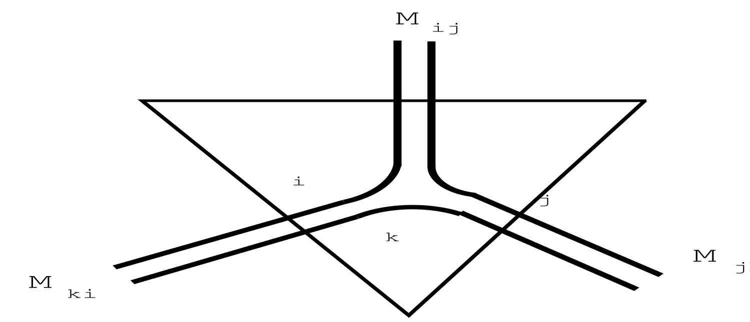

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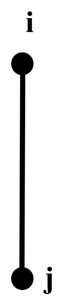

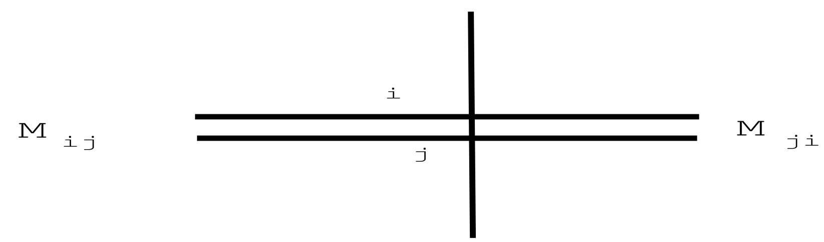

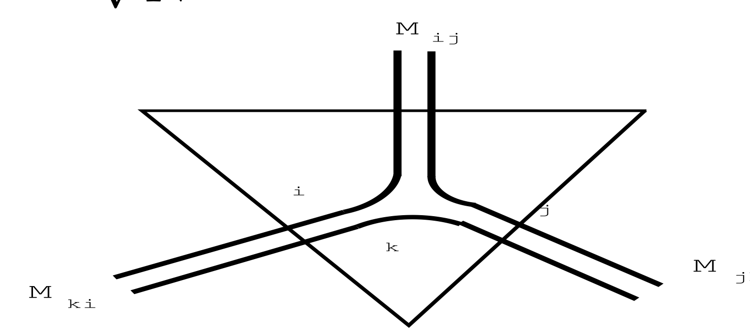

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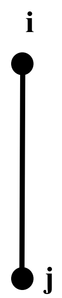

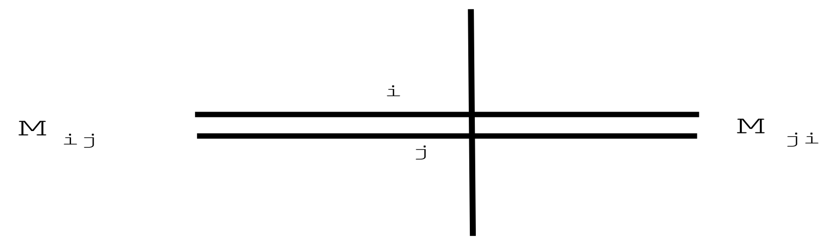

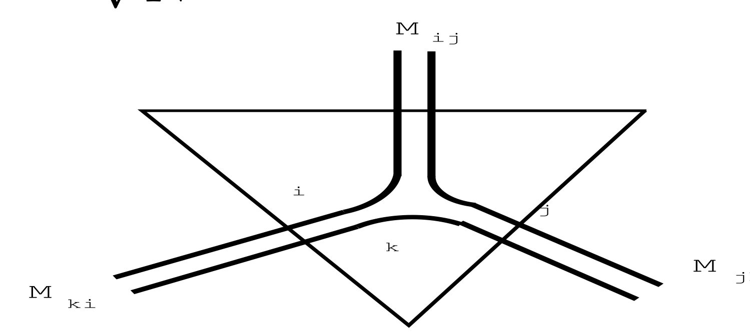

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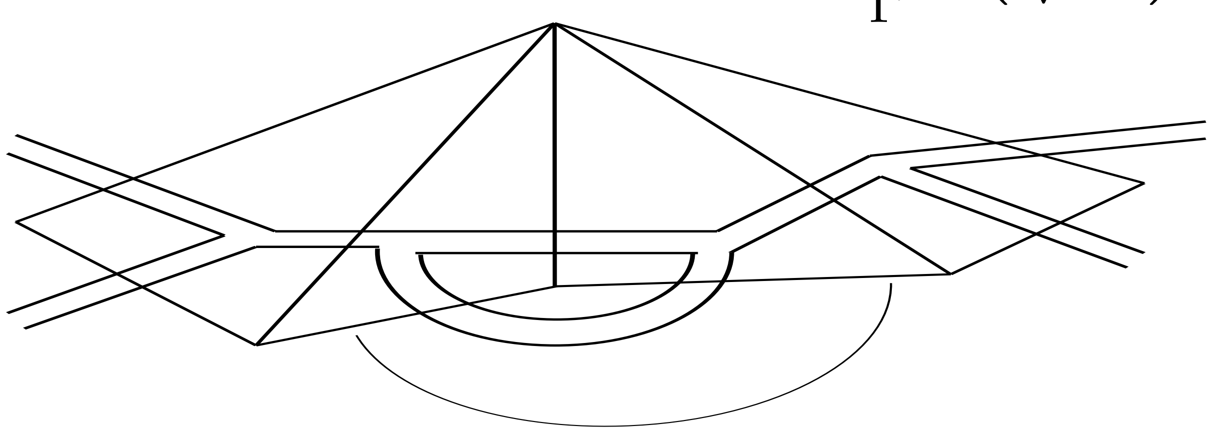

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e.g. d=3

Feynman diagrams are stranded graphs dual to 3d simplicial complexes

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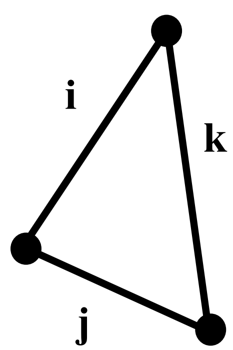

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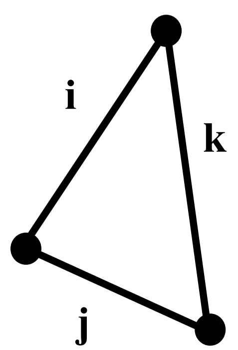

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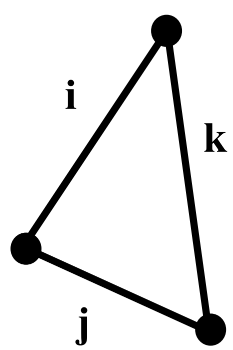

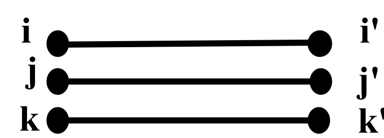

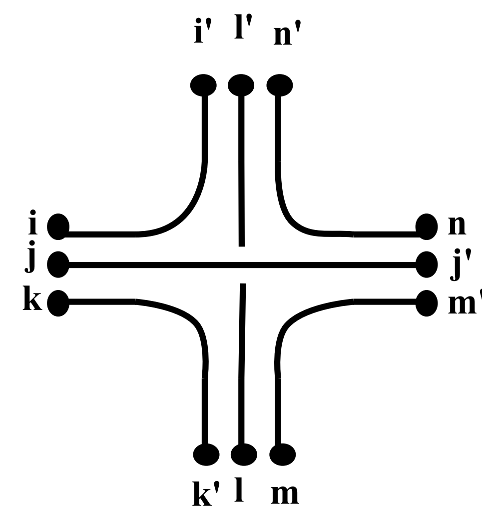

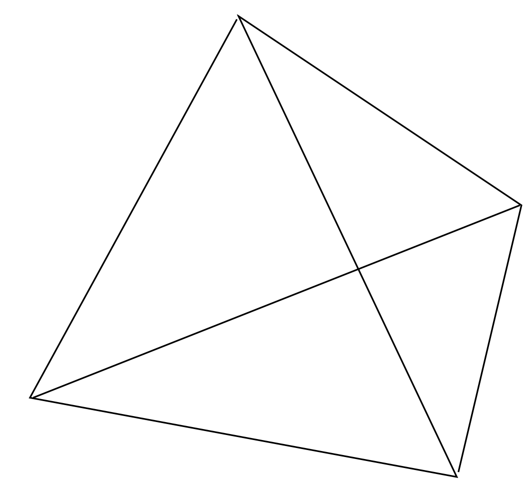

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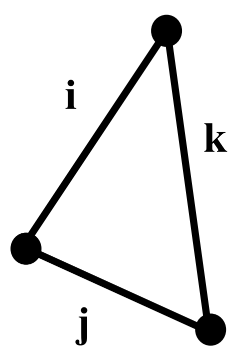

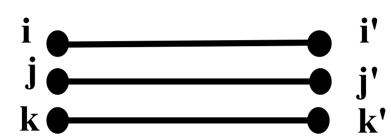

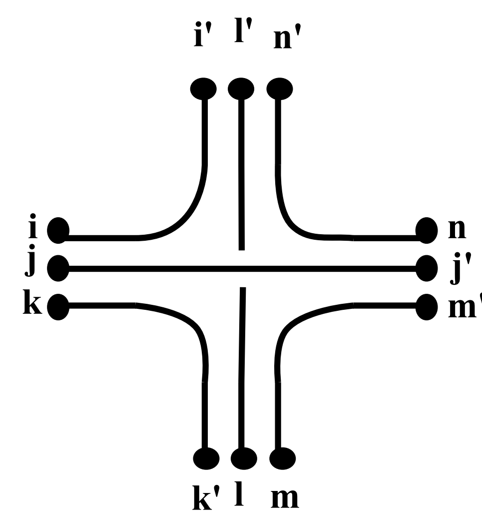

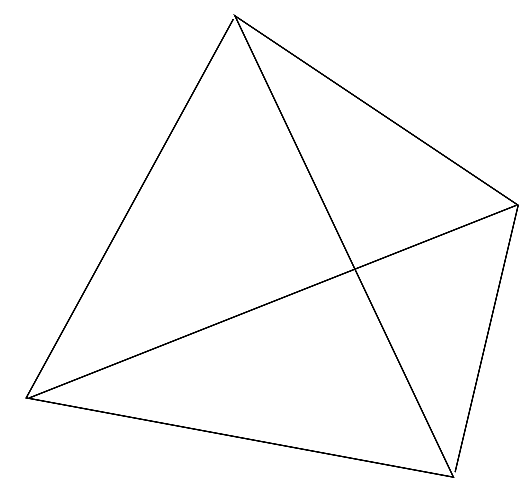

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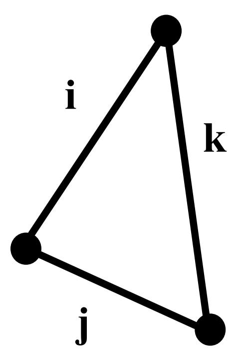

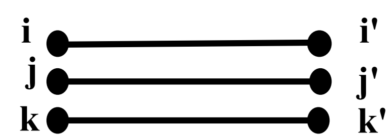

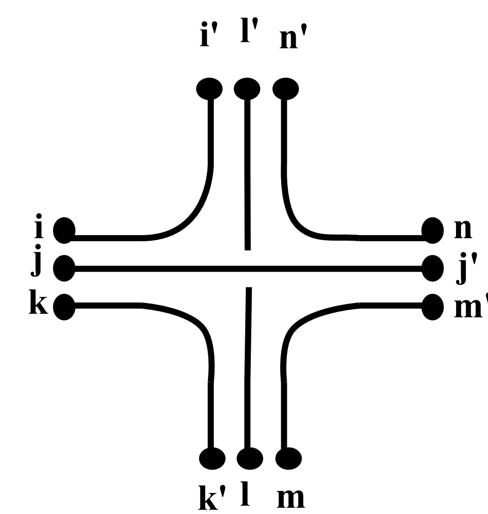

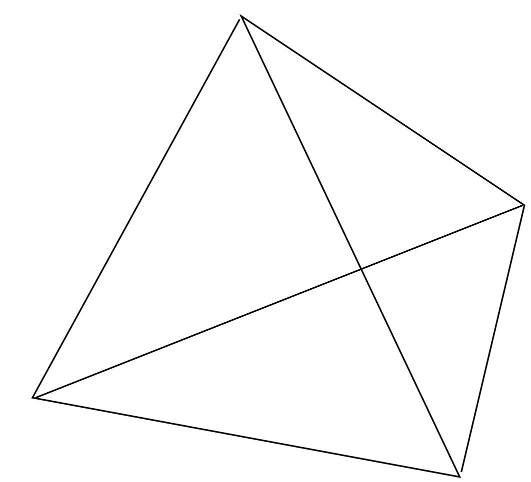

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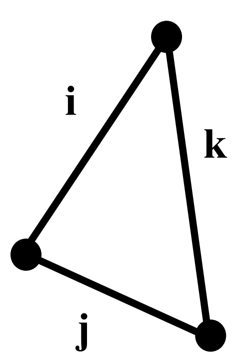

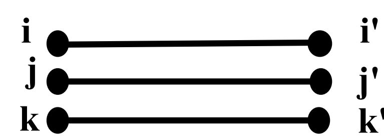

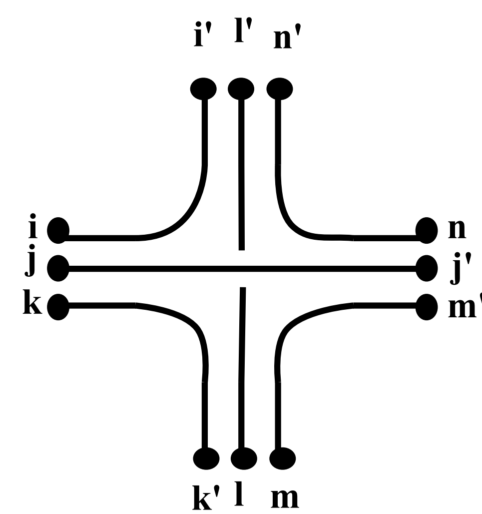

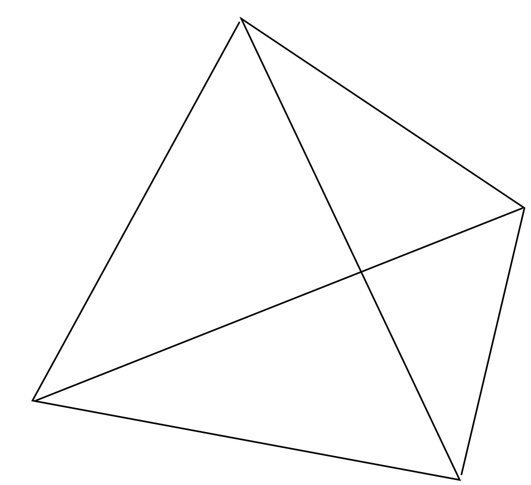

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Construction can be generalized to d spacetime dimension (d-tensors....)

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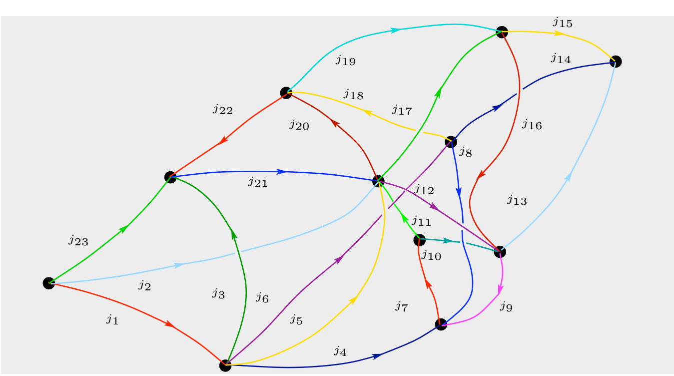
(Boulatov, Ooguri, De Pietri, Freidel, Krasnov, Rovelli, Perez, DO, Livine, Baratin, ……)

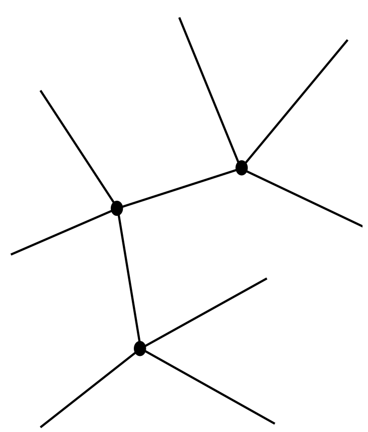
Quantum field theories over group G, enriching tensor models with group-theory data $\varphi : G^{\times d} \rightarrow \mathbb{C}$

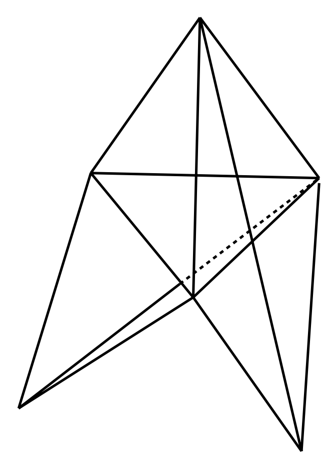
for gravity models, G = local gauge group of gravity (e.g. Lorentz group)

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

single field "quantum": spin network vertex or tetrahedron







generic quantum state: arbitrary collection of spin network vertices (including glued ones) or tetrahedra (including glued ones)

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quantum states are 2nd quantised spin networks/simplices

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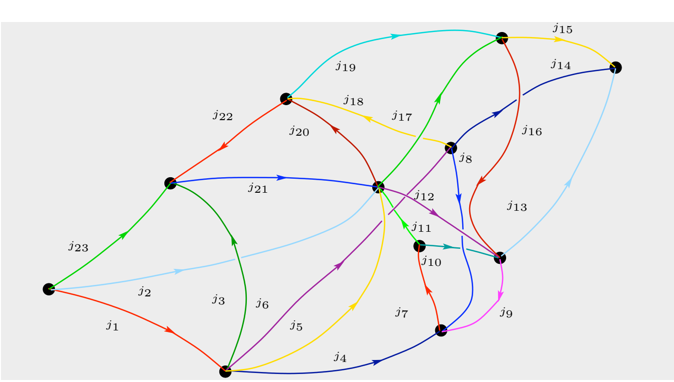

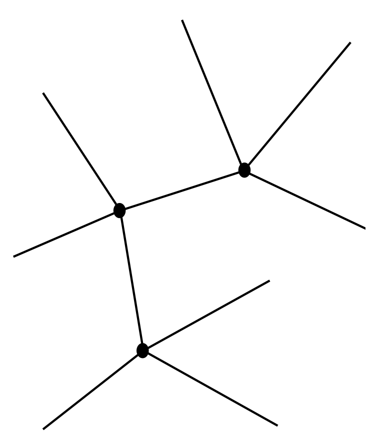

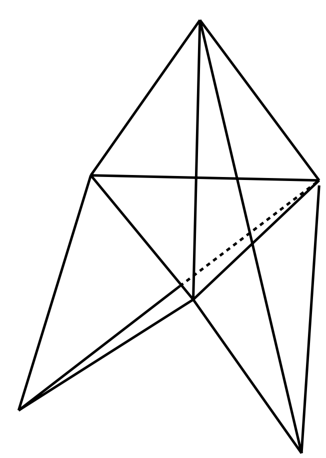

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Feynman perturbative expansion around trivial vacuum

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= stranded diagrams dual to cellular complexes of arbitrary topology

(simplicial case: simplicial complexes obtained by gluing d-simplices)

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Feynman amplitudes (model-dependent):

equivalently:

- spin foam models (sum-over-histories of spin networks ~ covariant LQG)

  Reisenberger,Rovelli, '00
- lattice path integrals (with group+Lie algebra variables)

  A. Baratin, DO, '11

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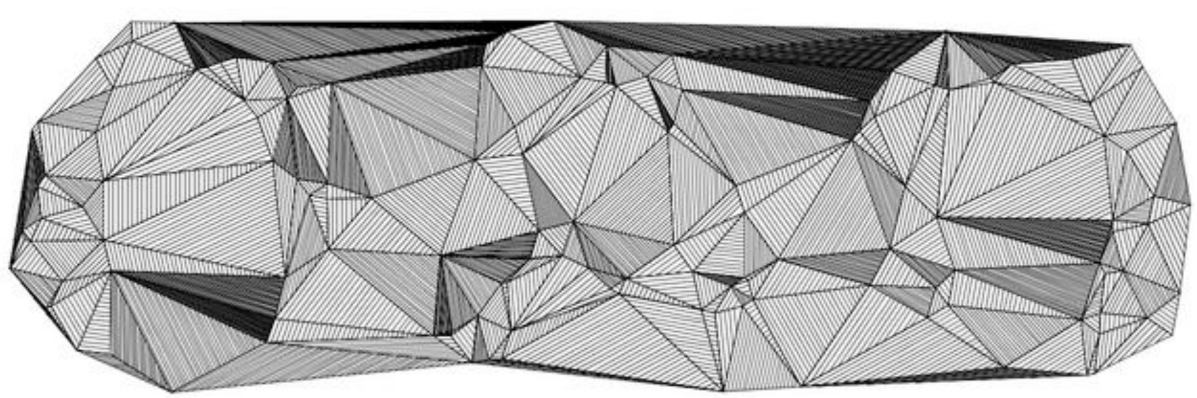

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GFT as lattice quantum gravity:

dynamical triangulations + quantum Regge calculus

....and more……

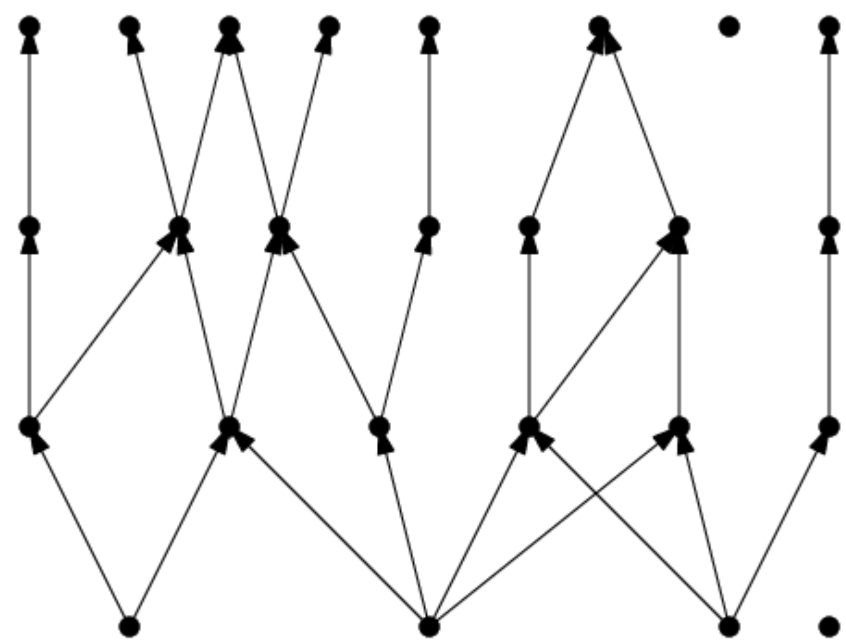
there are quite a few other quantum gravity approaches, with different goals and different levels of development

non-commutative geometry

algebras of functions (incl. coordinate functions) on spacetime are central object; they are turned into non-commutative algebras, thus “non-commutative spacetime and geometry”; 2 subdirections: Connes’ spectral triple (based on Dirac operator; possible route to unification) and “quantum spacetimes” (based on Hopf algebra symmetries, basis of much phenomenology); difficult to turn on dynamics of geometry and spacetime itself

causal set theory

intrinsically discrete sub-structure for spacetime, given by fundamental causal relations between finite set of “events”, giving a “partially ordered, locally finite set”. quantum dynamics defined ideally by “sum-over-causets” weighted by quantum amplitude; continuum spacetime should emerge from this sum, as approximation



quantum graphity, twistor theory, ….

not going to discuss them here…..

other thing that happened:

birth and development of Quantum Gravity phenomenology

in general sense of: clarification of physical contexts and regimes in which quantum gravity effects could be relevant and preliminary characterisation of such effects

this includes:

- purpose-built phenomenological models/scenarios trying to incorporate QG ideas
- modelling of extreme physical systems within or (more often) inspired by specific QG approaches
- altogether new QG ideas implemented in toy models, waiting for realization in full QG formalisms

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QG phenomenology

many (simplified) scenarios are already testable

- minimal length
- deformed uncertainty relations

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

- 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

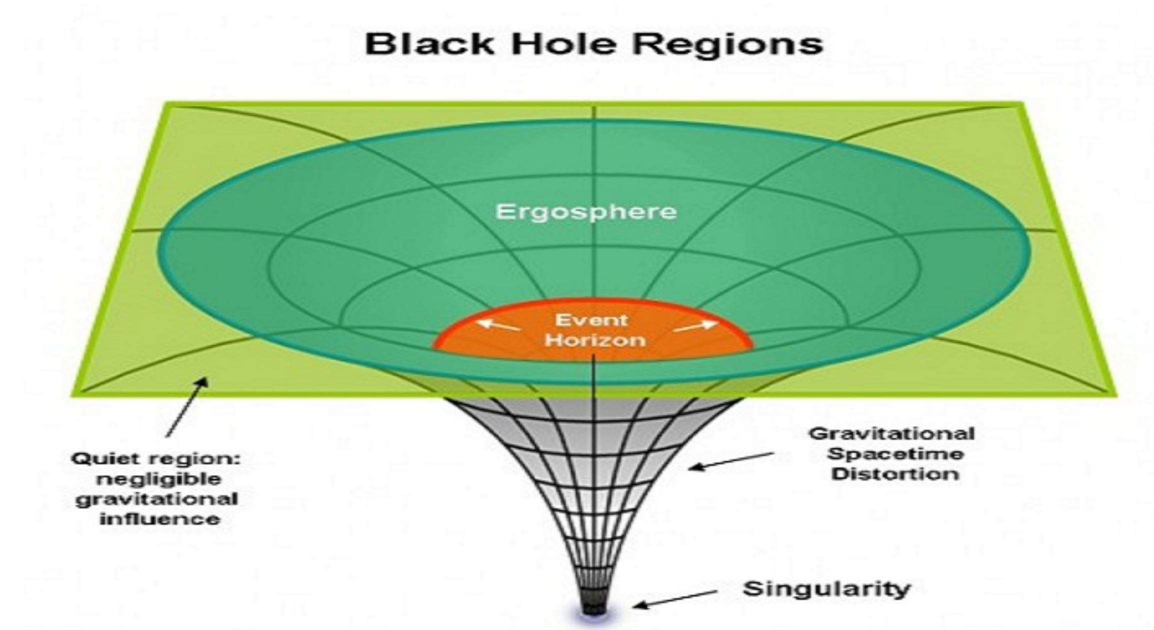
$$m^2 \approx E^2 - \vec{p}^{\,2} + \alpha\left(\frac{E}{m_{\rm p}}\right) E^2$$

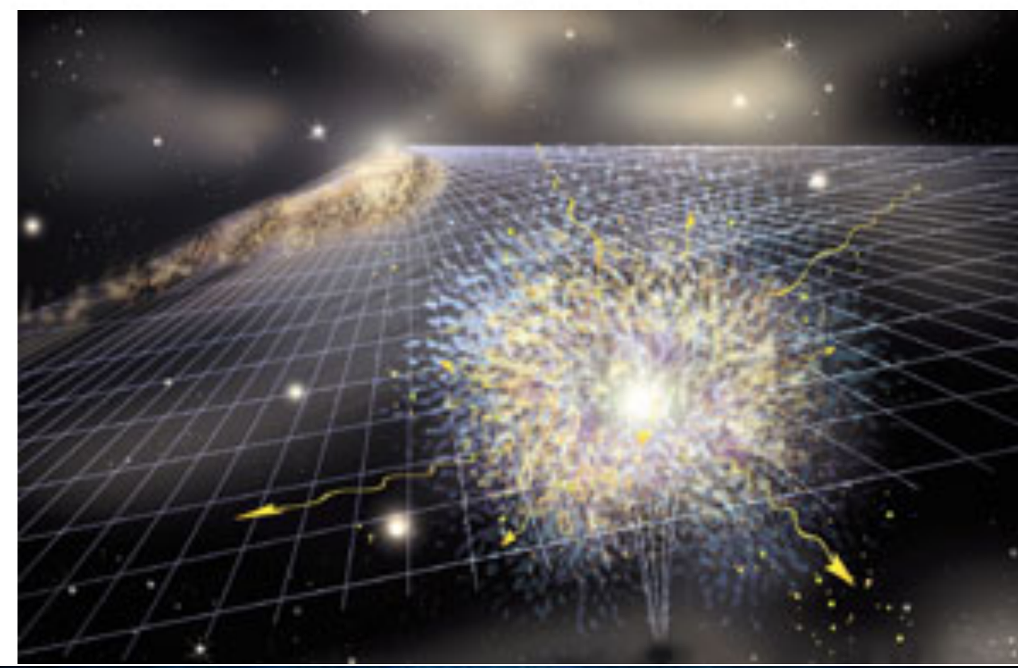
- modified scattering thresholds
- non-local terms (violation of locality)

QG effects in black hole physics

many, many possibilities, among which:

- 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





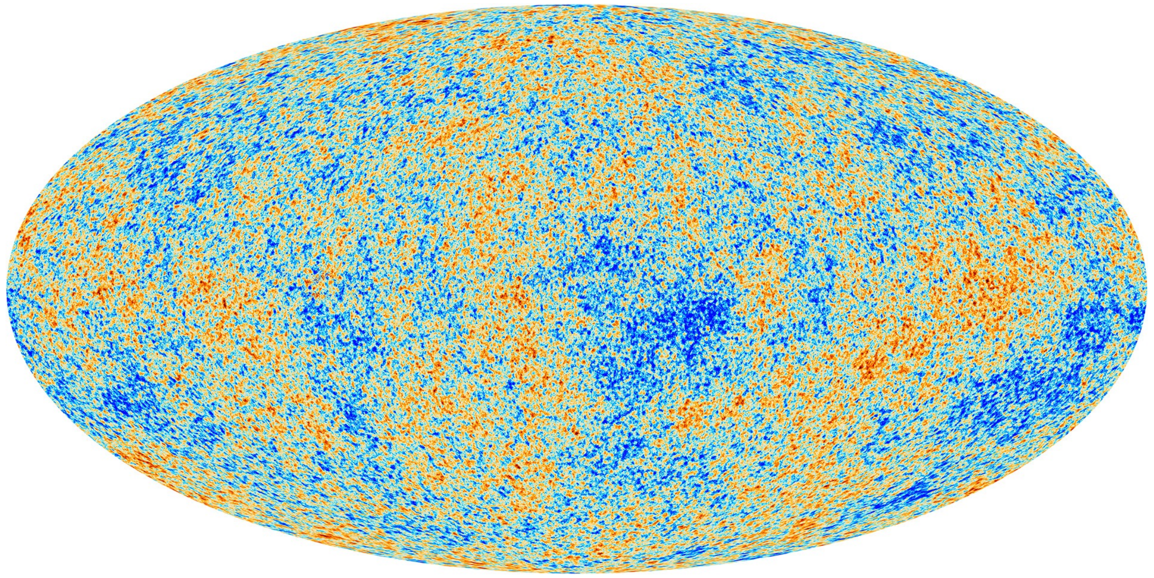
QG in cosmological scenarios for the early universe

why a close to homogeneous and isotropic universe?

why an approximately scale invariant power spectrum?

what is the fine. structure of the CMB spectrum?

R. Brandenberger, ’10, ’11, ’14

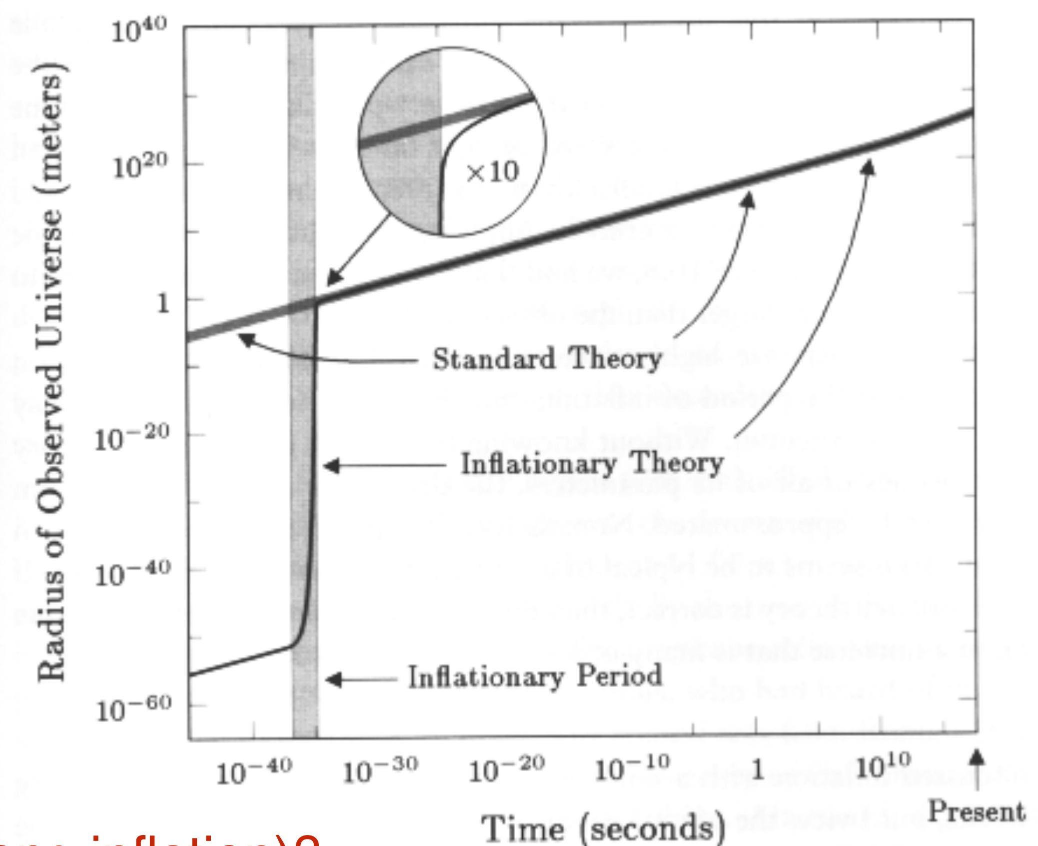


Inflation

Bouncing cosmology

Emergent universe

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



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

Inflation needs Quantum Gravity

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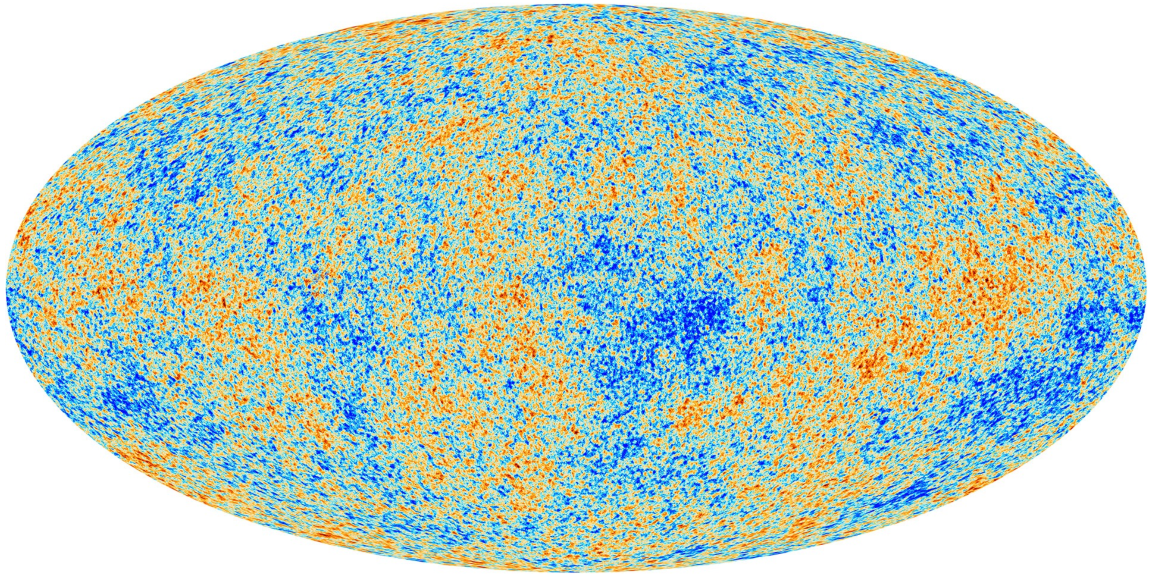

Inflation

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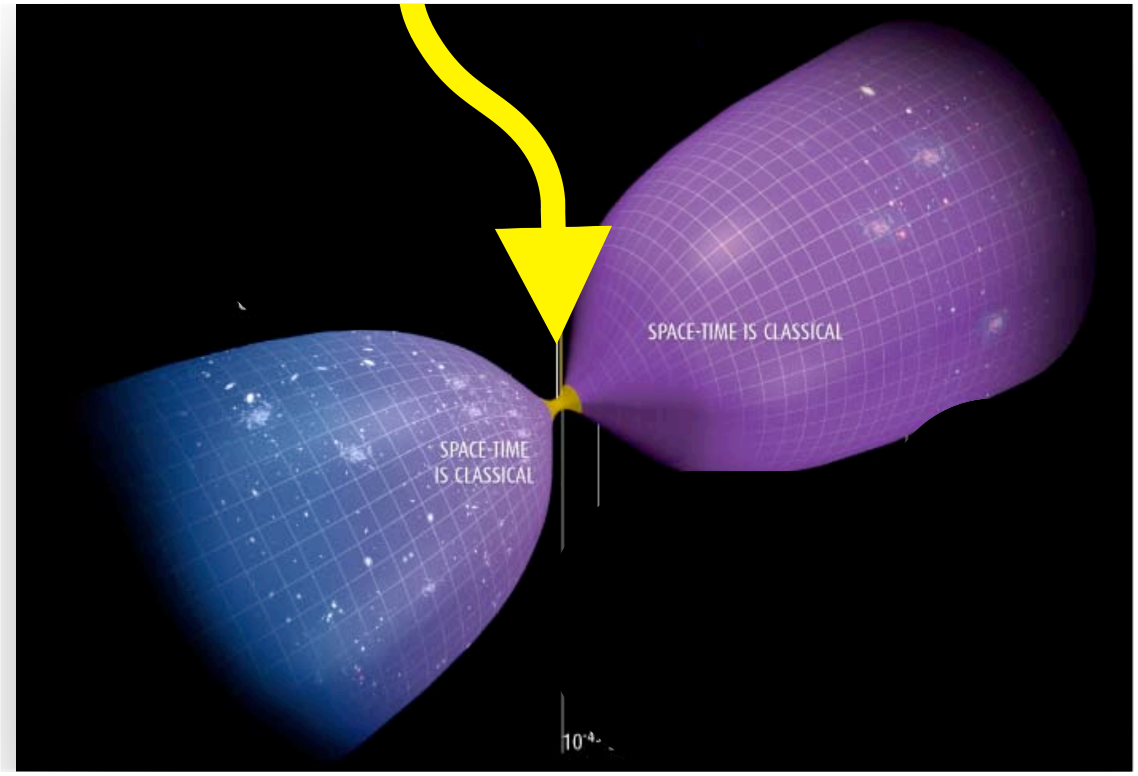

- classical contracting phase “before” the big bang, bouncing to current expanding phase
- various realizations (e.g. LQC)
- can produce scale invariant spectrum
- new physics needed to describe/justify cosmological bounce

Bouncing cosmology needs Quantum Gravity

QG in cosmological scenarios for the early universe

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why an approximately scale invariant power spectrum?

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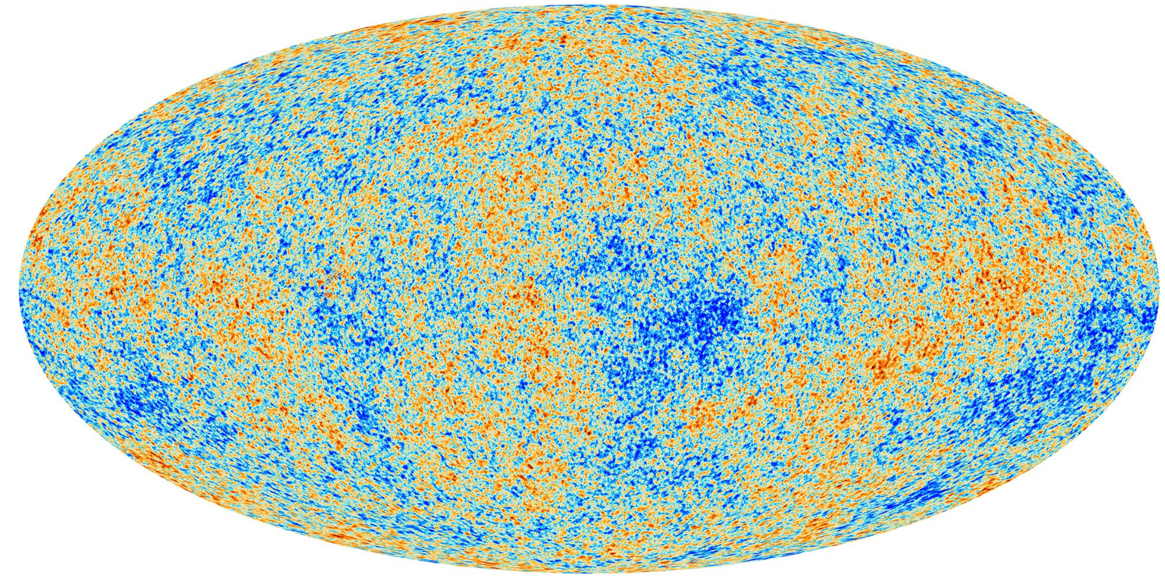
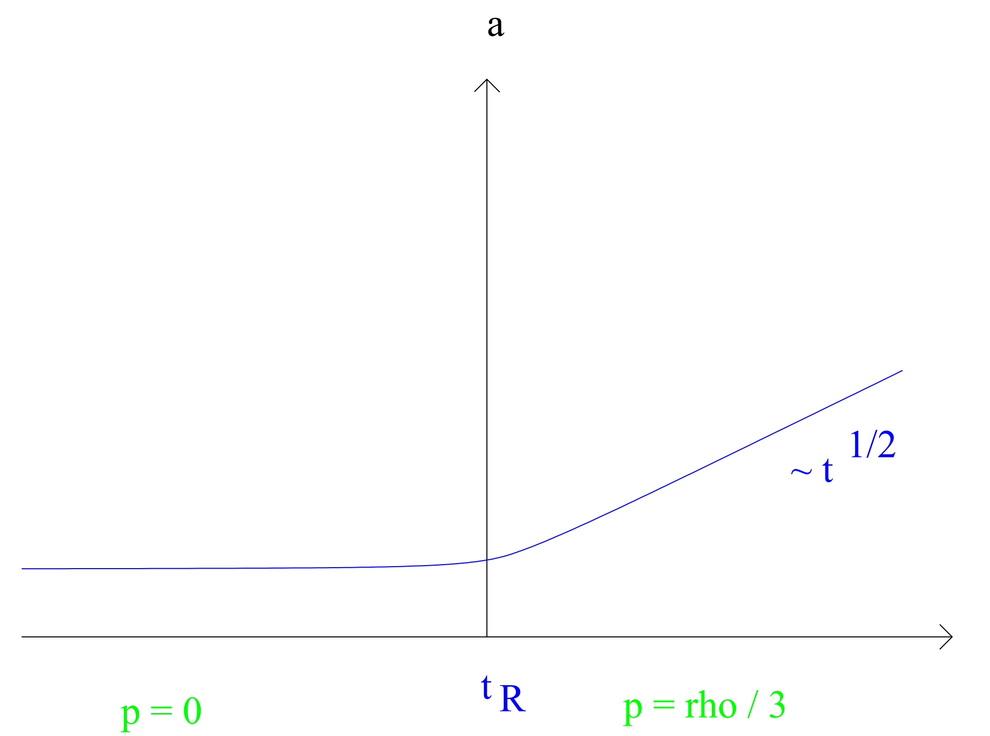


Inflation

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



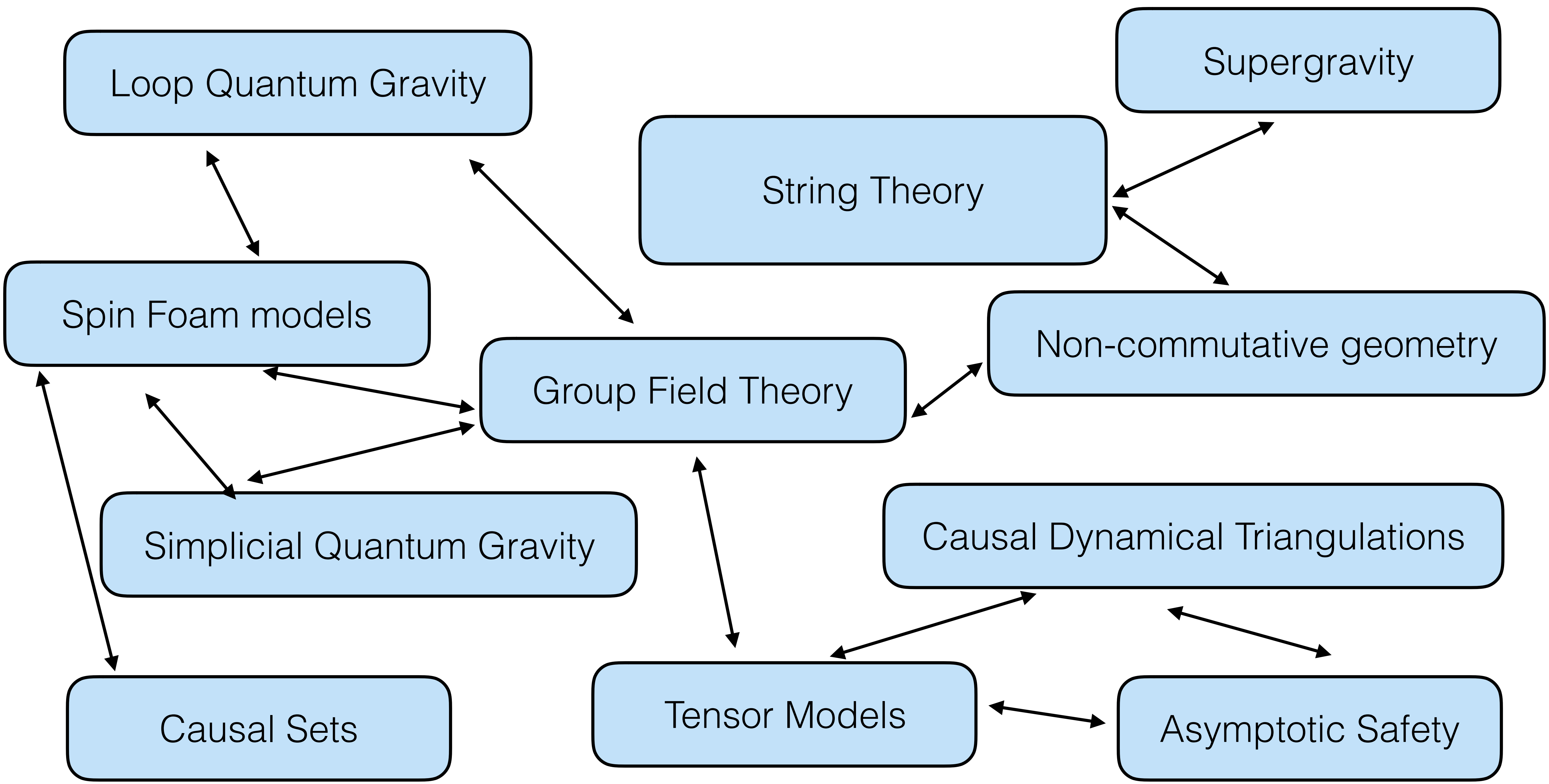
Emergent universe needs Quantum Gravity

Quantum Gravity:
the picture now

(“now” ~ last 10 years)

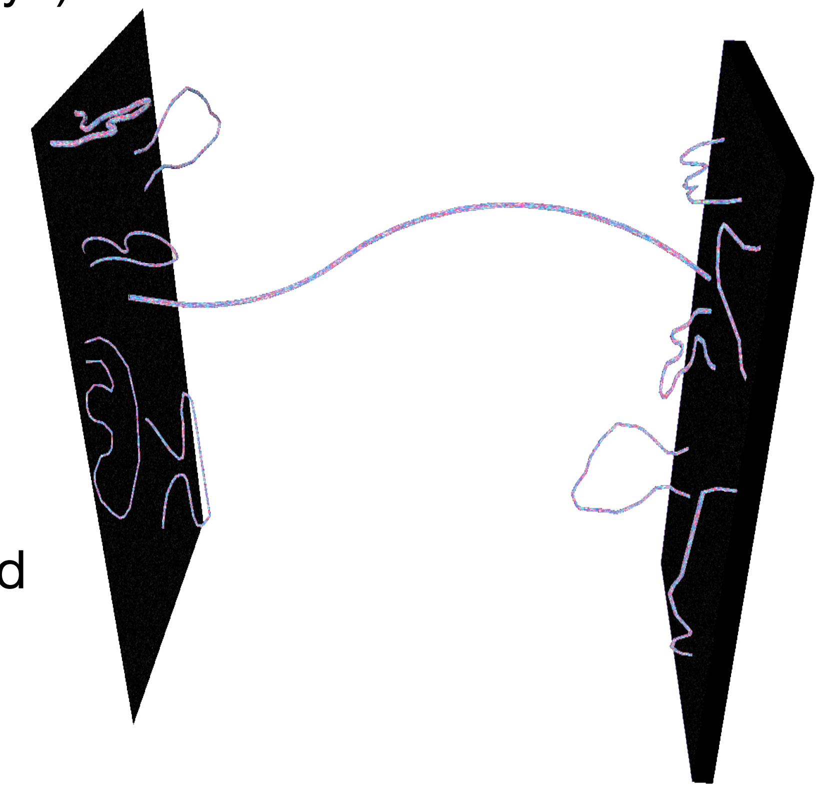
Quantum Gravity: many approaches

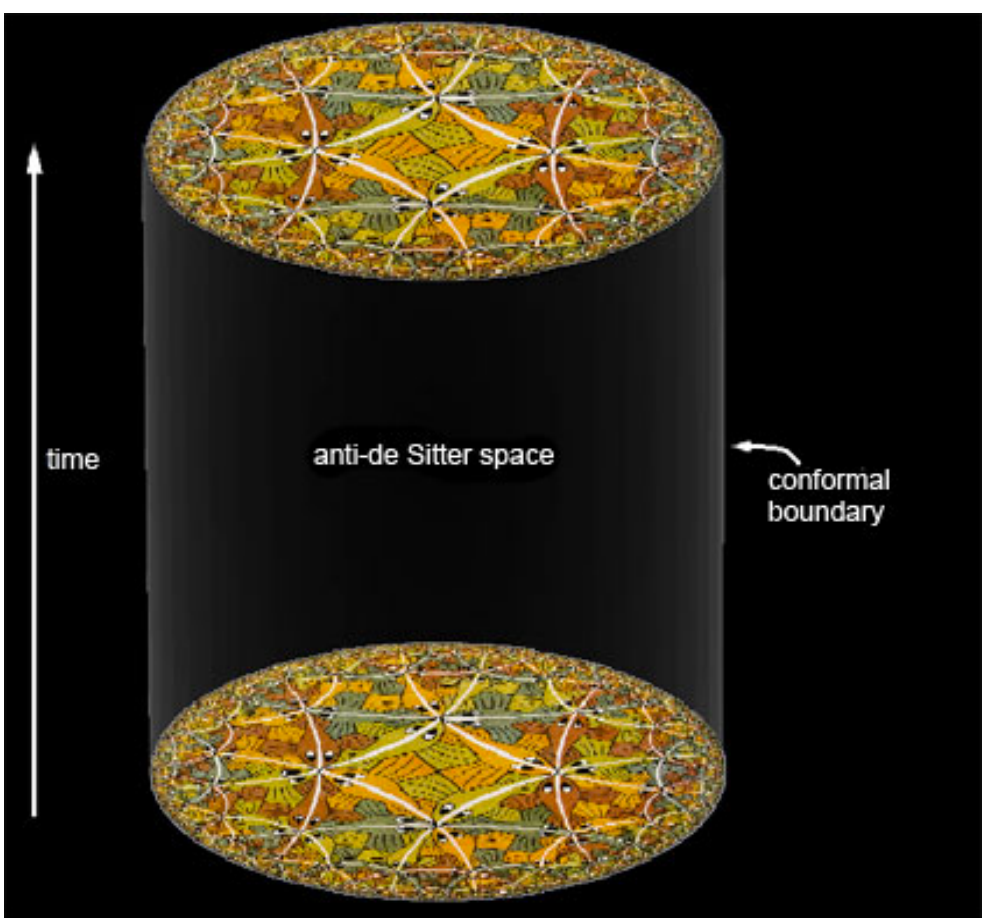
several links between them; solid foundations, many achievements, big outstanding open issues in each



The Theory Formerly Known As String Theory (and not yet become M-Theory)

- vast array of mathematical results and constructions (a framework or a theory?)
- landscape of possible theories
- generalised geometries and dualities suggest fundamental theory (if any) not based on spacetime
- incredibly rich and providing suggestions and new insights into both QFT and gravitational physics
- AdS/CFT offering testing ground for many QG ideas (and quantum BH physics)

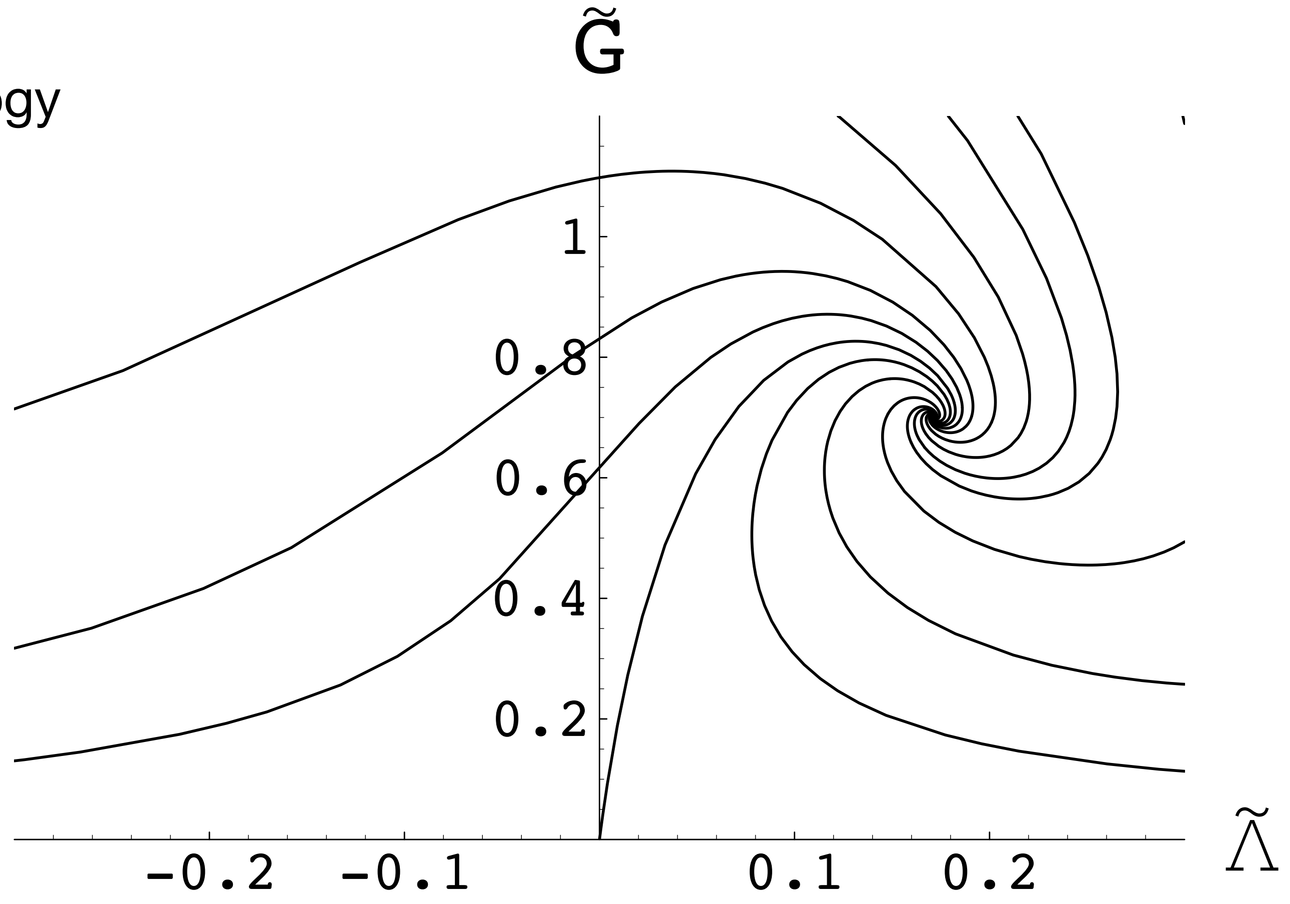




- fundamental degrees of freedom and dynamics still elusive
- no non-perturbative quantum formulation (of strings and/or branes)
- new connections to quantum information
- inspiration for model building in particle physics and cosmology
- still no strong prediction that could test it

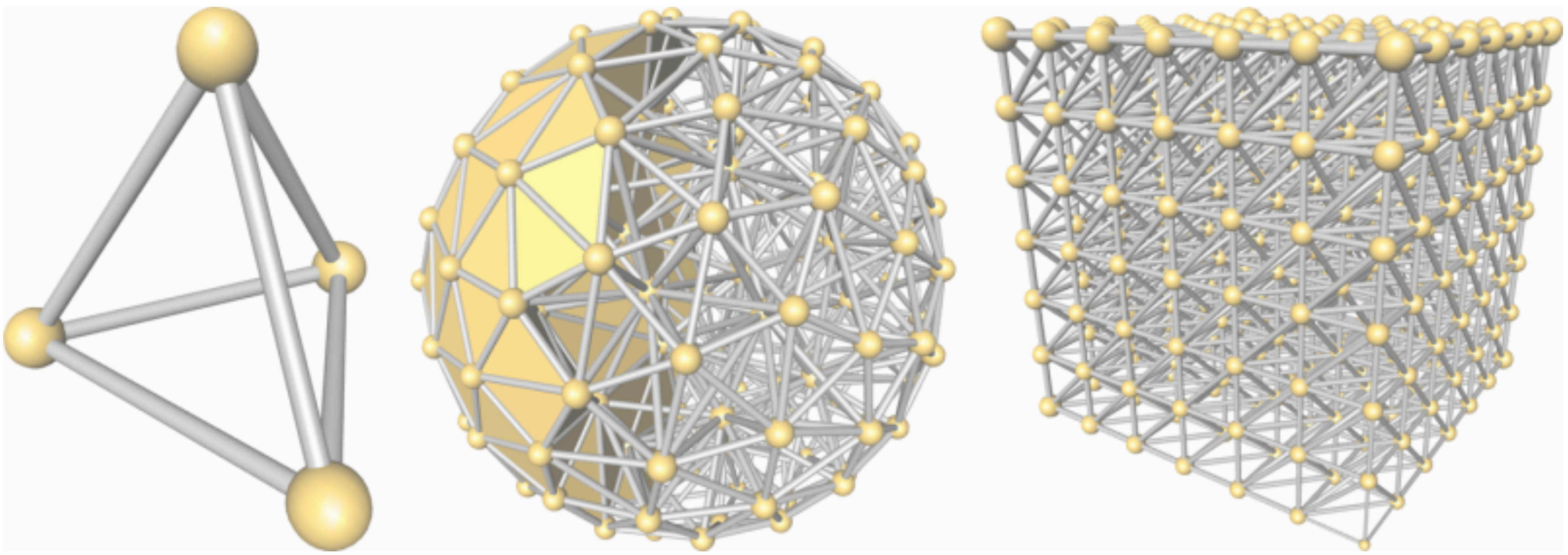
Asymptotic Safety scenario

- evidence for UV non-Gaussian fixed point keeps accumulating
- formalism applied also to QG extensions of Standard Model, offering glimpses of possible QG solutions to various puzzles (hierarchy, matter content, …)
- extension to Lorentzian setting
- details on implementation of diffeomorphism symmetry
- applications to quantum black holes and cosmology



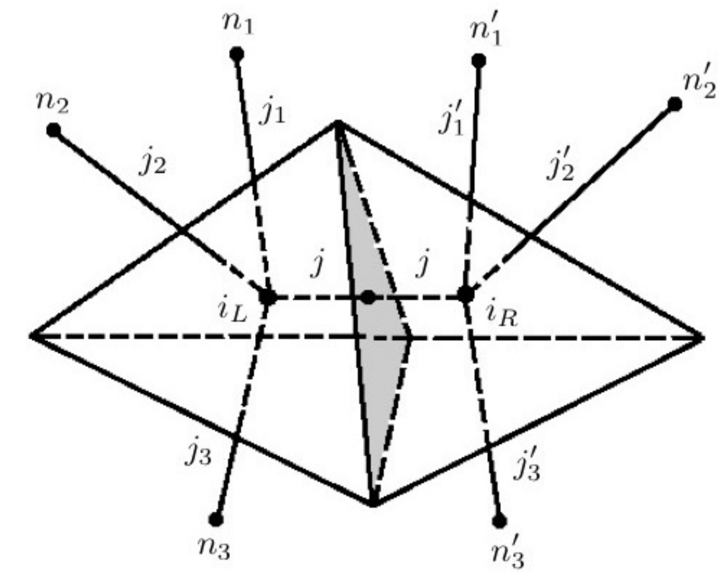
Causal Dynamical Triangulations

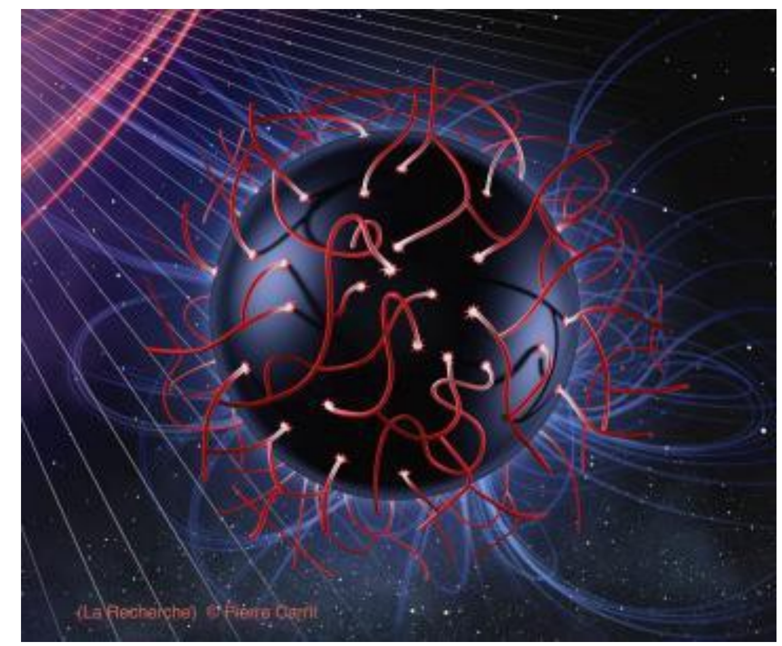
- increasing experience with (numerical) estimate of various geometric observables
- solid evidence of continuum phase structure, with at least one geometric (De Sitter) phase
- evidence of dimensional flow
- continuum limit seems to give Horava gravity
- results on relaxing global causality restrictions in favour of local ones



Loop Quantum Gravity and Spin Foam models

- solid kinematical structure (canonical quantization may work, after all)
- stronger link with discrete (lattice) quantum gravity
- new kinematical phases; studies of entanglement and other QI for spin networks (connections to tensor networks)
- nice and rich quantum geometry, beautiful mathematics, connections to quantum groups
- still no satisfactory continuum quantum dynamics (under control with clear relation with GR)
- intriguing models of cosmology, black holes, possible phenomenology; but yet to be derived from (or grounded within) fundamental theory
- lots of recent work on coarse graining and renormalization (mostly in spin foam context)
- yet to show that it has good continuum limit, giving rise to effective QFT (incl. gravitons) as approximation





Tensorial group field theories

- increased understanding of link with LQG and. discrete QG

- connections to non-commutative geometry and to tensor networks

- large N limit: control over topologies, dominance of melonic diagrams, critical behaviour in tensor models

- many renormalization studies: renormalizability of various models, asymptotic freedom/safety

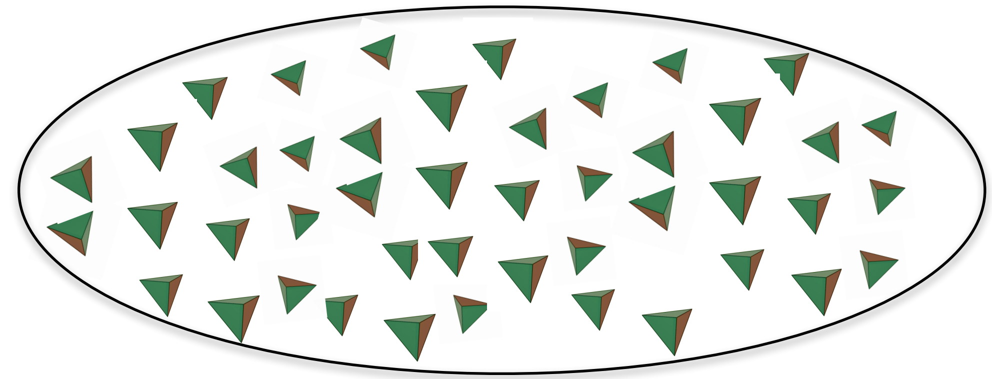
- glimpses of continuum phase diagram, via functional RG methods

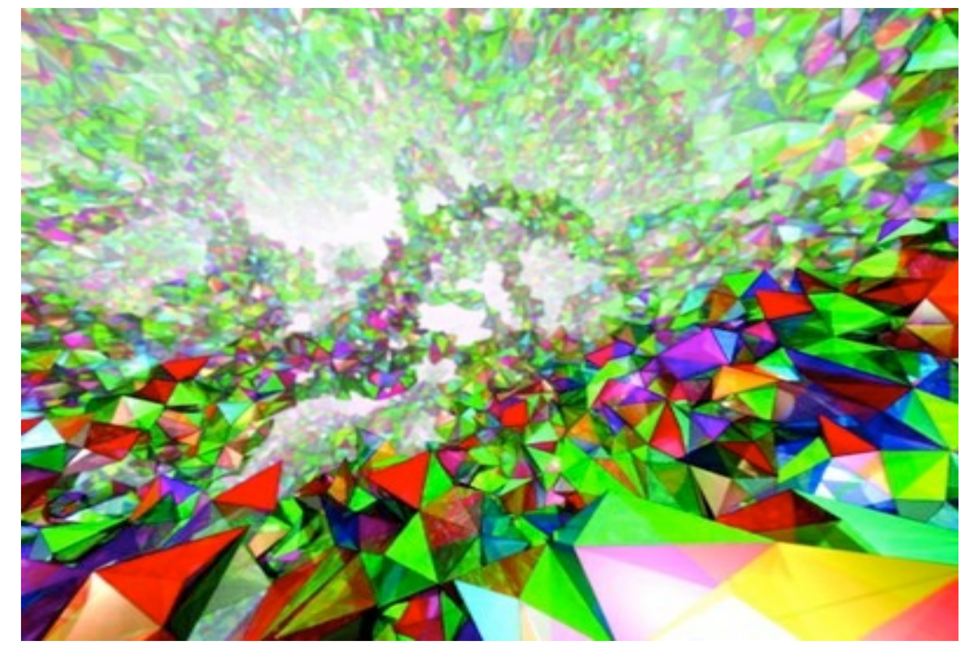
- applications to SYK models and AdS/CFT

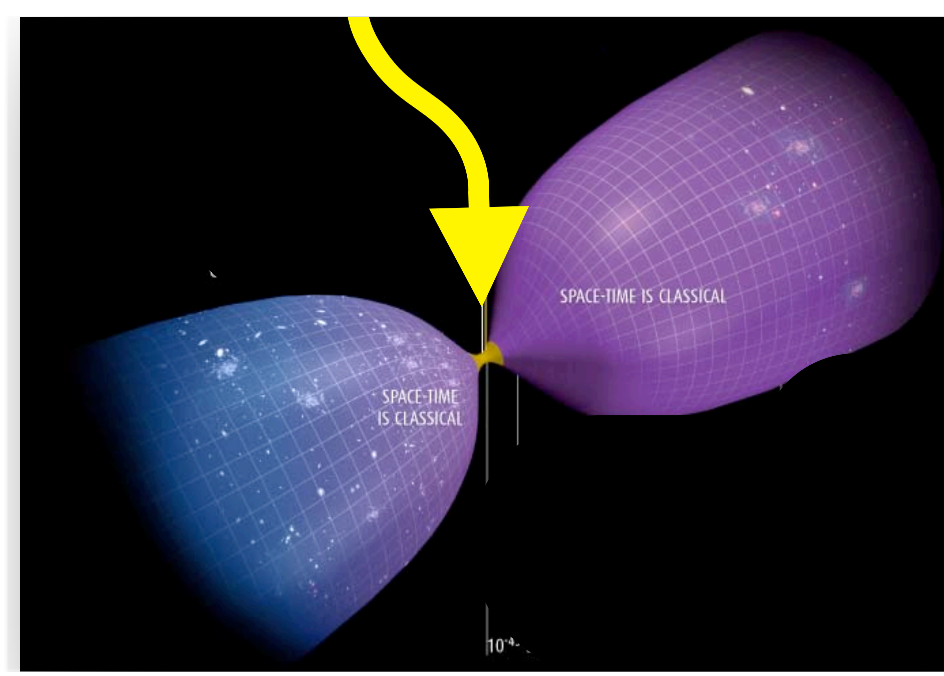
- emergent cosmological dynamics from GFT condensates (consistent continuum limit, quantum bounce)

- modelling of quantum black holes and area law within full theory

- still no proof that effective continuum theory is (approximately) QFT of gravitons or full GR







new trends and suggestions

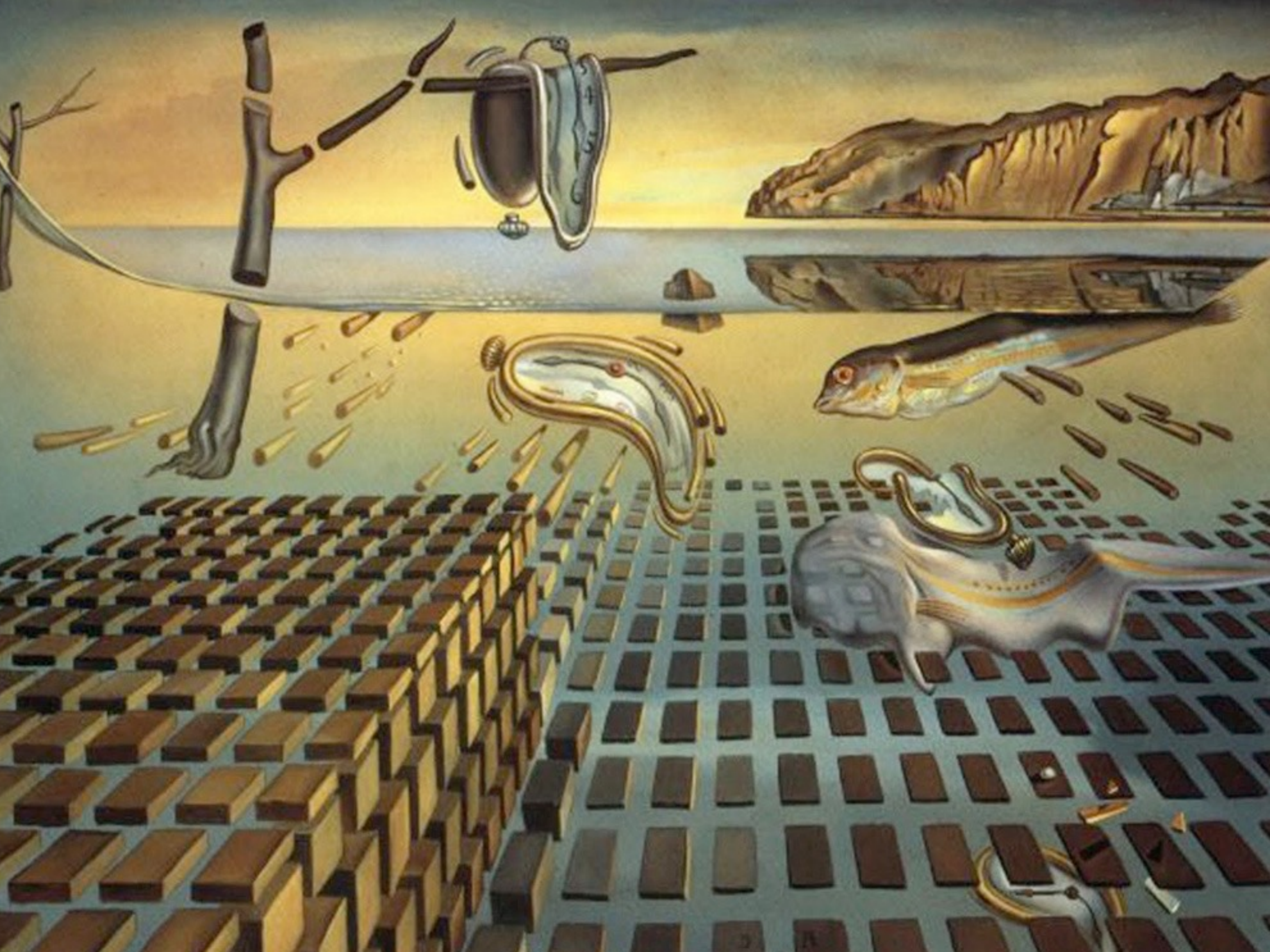
new suggestions for fundamental QG physics, possibly common to several QG approaches, have emerged and have been taken into account in various QG formalisms

all of them indicate a universe which is, at the fundamental level, even stranger than we thought; they also indicate that the scope of Quantum Gravity may go well beyond what we had imagined

Beyond spacetime? hints from various corners

- challenges to "localization" in semi-classical GR — minimal length scenarios
- spacetime singularities in GR — breakdown of continuum itself?
- black hole thermodynamics — space itself is a thermodynamic system
- black hole information paradox — some fundamental principle has to go: locality?
- Einstein's equations as equation of state
  GR dynamics is effective equation of state for any microscopic dofs collectively described by a spacetime, a metric and some matter fields
- entanglement ~ geometry
  geometric quantities defined by quantum (information) notions (examples from AdS/CFT, and various quantum many-body systems)

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



Spacetime and its atomic constituents

Spacetime is emergent

and made out of non-spatiotemporal quantum building blocks

("atoms of space")

supporting (indirect) evidence/arguments:

- QG approaches (e.g. LQG/GFT spin networks)
- string theory dualities (incl. AdS/CFT)
- BH entropy (finite) and thermodynamics
- GR singularities (breakdown of continuum?)

quantum space as a (background-independent) quantum many-body system

Quantum Gravity: new perspective

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

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

↓

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

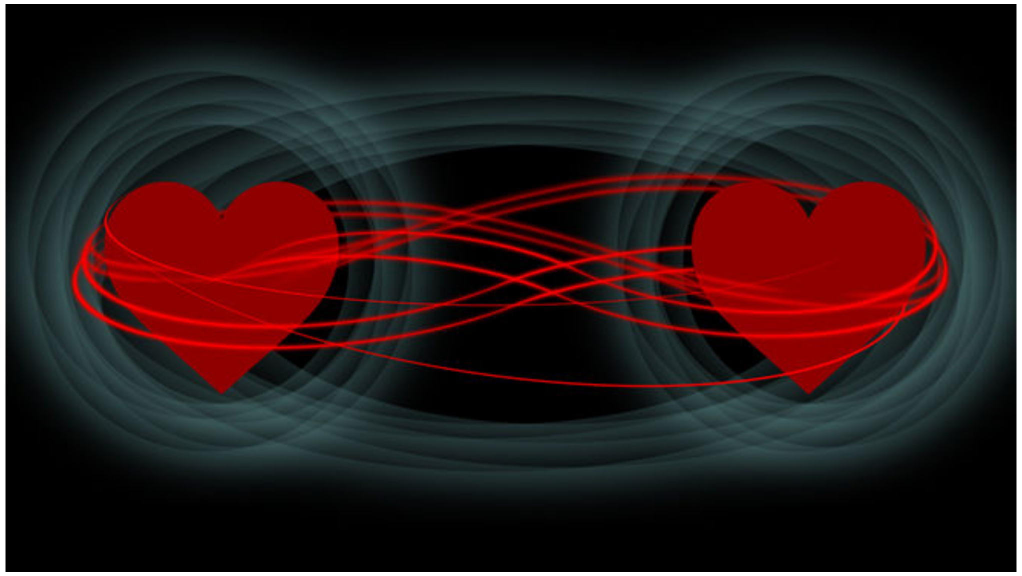
problem becomes similar to the typical one in condensed matter theory (from atoms to macroscopic physics)

entanglement/geometry correspondence

If spacetime is emergent, which quantum features of the fundamental entities are responsible for its geometric properties?

Many recent results put in direct correspondence geometric quantities (distances, areas, etc) with quantum entanglement between the constituents of non-gravitational systems.

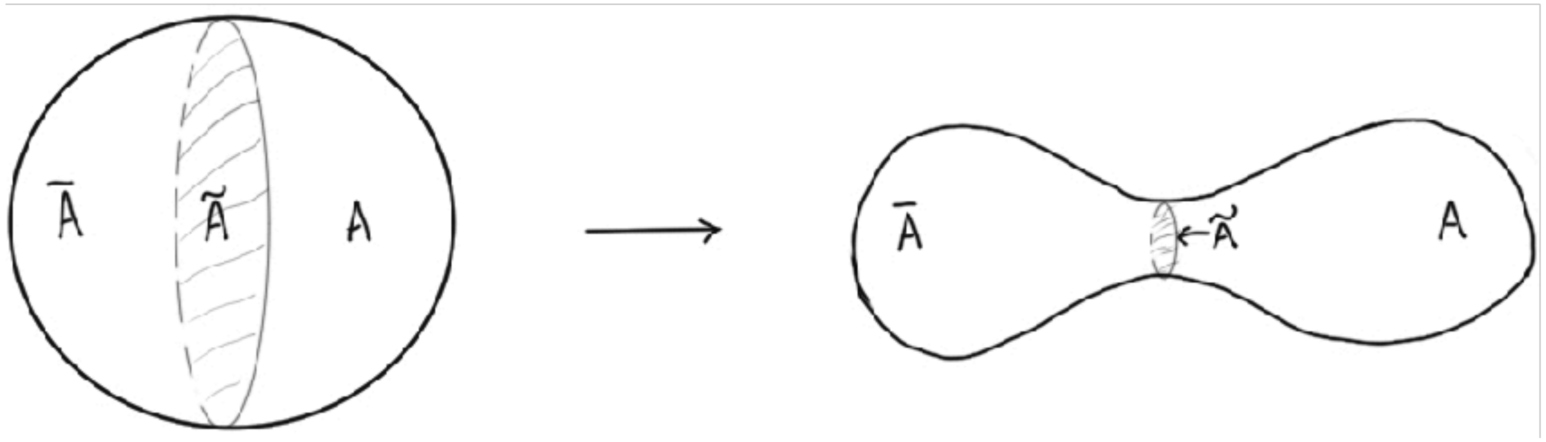
Is the world “made out of entanglement”? Is geometry just quantum information at its root?



many results in the context of AdS/CFT correspondence but suggestion is more radical than that

- spacetime bulk reconstruction from CFT quantum correlations between boundary regions

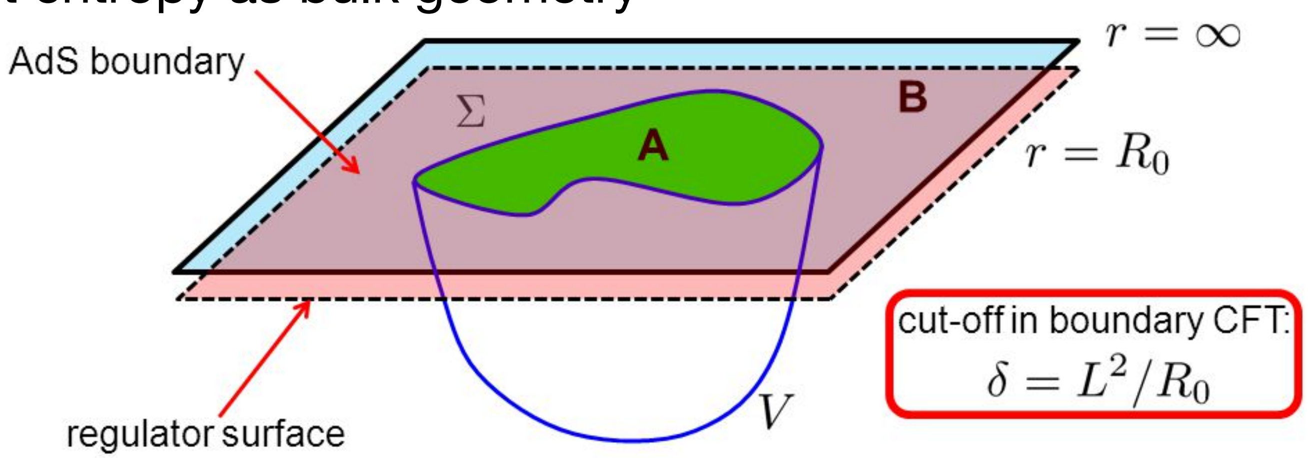
e.g. (mutual information) entanglement ~ spacetime connectivity



- holographic entanglement entropy - CFT entanglement entropy as bulk geometry

e.g. Ryu-Takayanagi entropy formula

Ryu-Takanayagi, ’06, ’12;
Miyaji-Takayanagi ’15



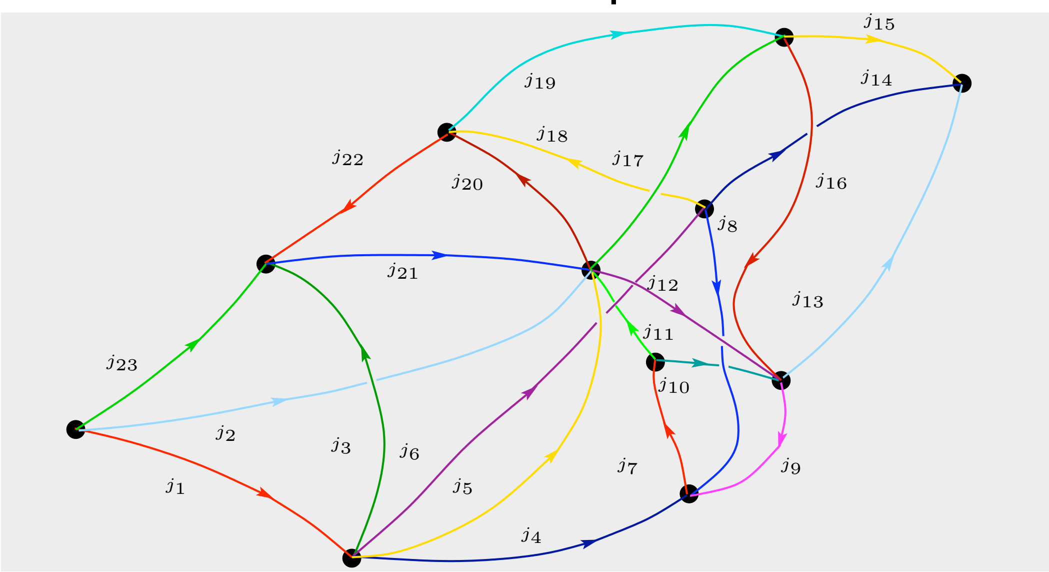
suggests generalization of BH entropy to other (arbitrary?) surfaces

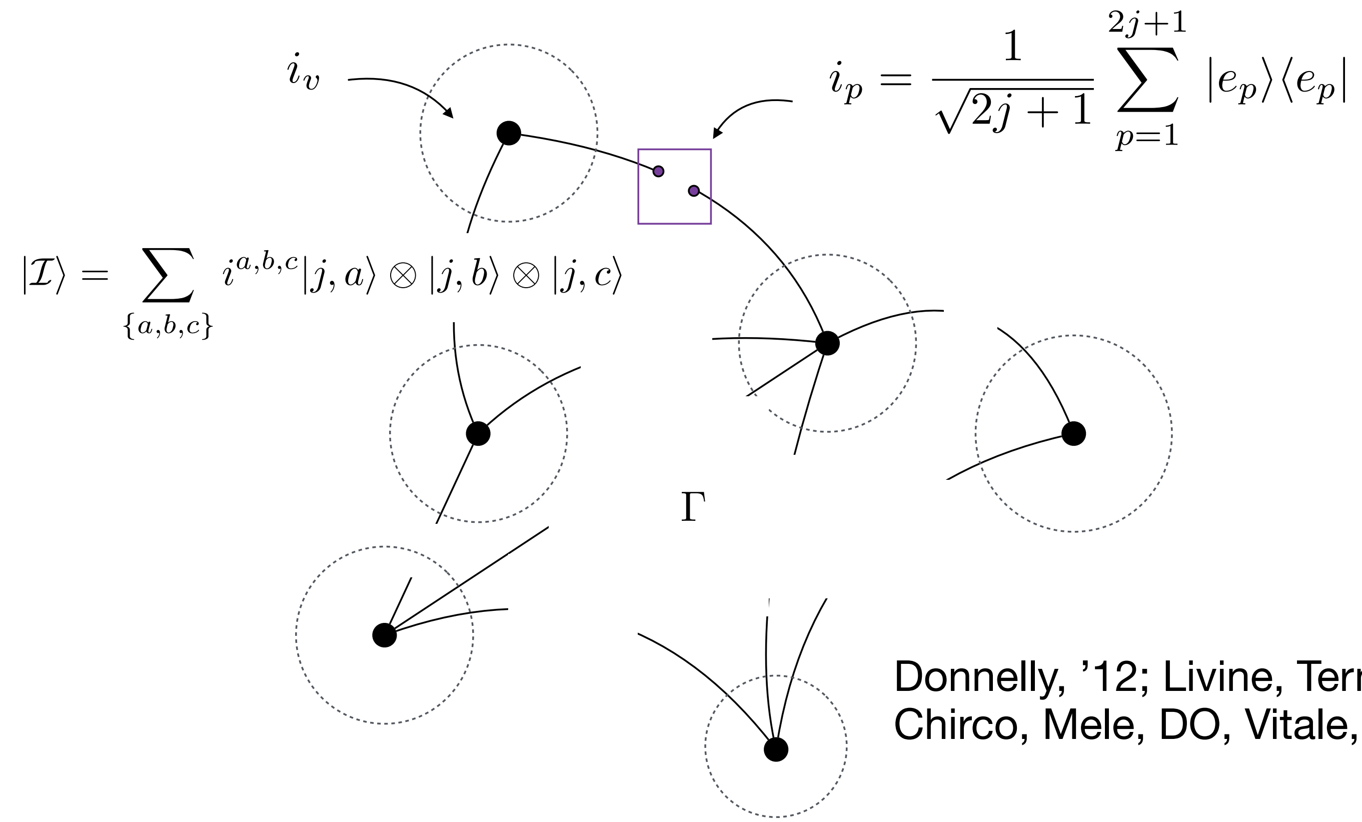
$$S(A) = \underset{\partial V = \Sigma}{\text{ext}} \frac{A_V}{4G_N}$$

Geometry from Quantum

examples from QG camp

- entanglement is encoded in connectivity structure of LQG/GFT spin networks





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

- area law for entanglement entropy as signal of good semi-classical behaviour in LQG states

Bianchi et al. '16, Chirco et al '14, '15, Hamma et al. '15, Bianchi, Myers 2012, Chirco, Anzà '16, Han et al. '16

- entanglement in black hole modelling and entropy calculations

Perez, Pranzetti, Ghosh, Bianchi, Livine, Terno, Sindoni, DO, …….

- coarse graining schemes for spin networks and spin foams based on entanglement (also via tensor networks)

Dittrich, Martin-Benito, Steinhaus, Charles, Livine, ….

- Ryu-Takanayagi formula in group field theory and holographic tensor networks

Chirco, Zhang, DO, '17, '18

QG phenomenology

new avenues toward testing QG effects

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)

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

Main theoretical problem:

most testable effects obtained within simplified models and phenomenological frameworks

very weak link with fundamental theory

pressing issue:

connect simplified models with fundamental formalisms

Quantum Gravity: looking ahead

optimistic and very biased forecast

not to be taken too seriously as forecast, maybe

to be taken seriously as wishful thinking

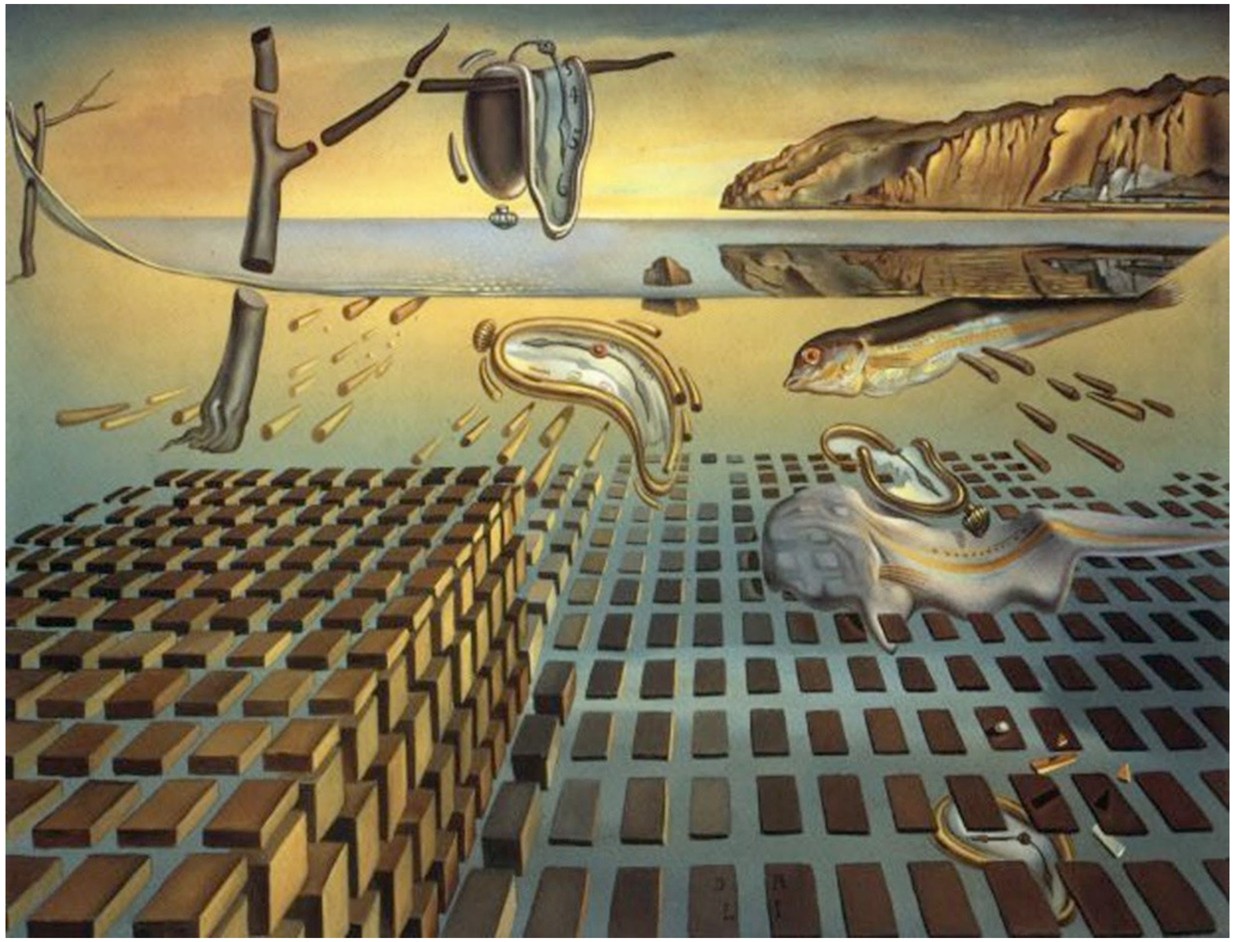
Beyond spacetime

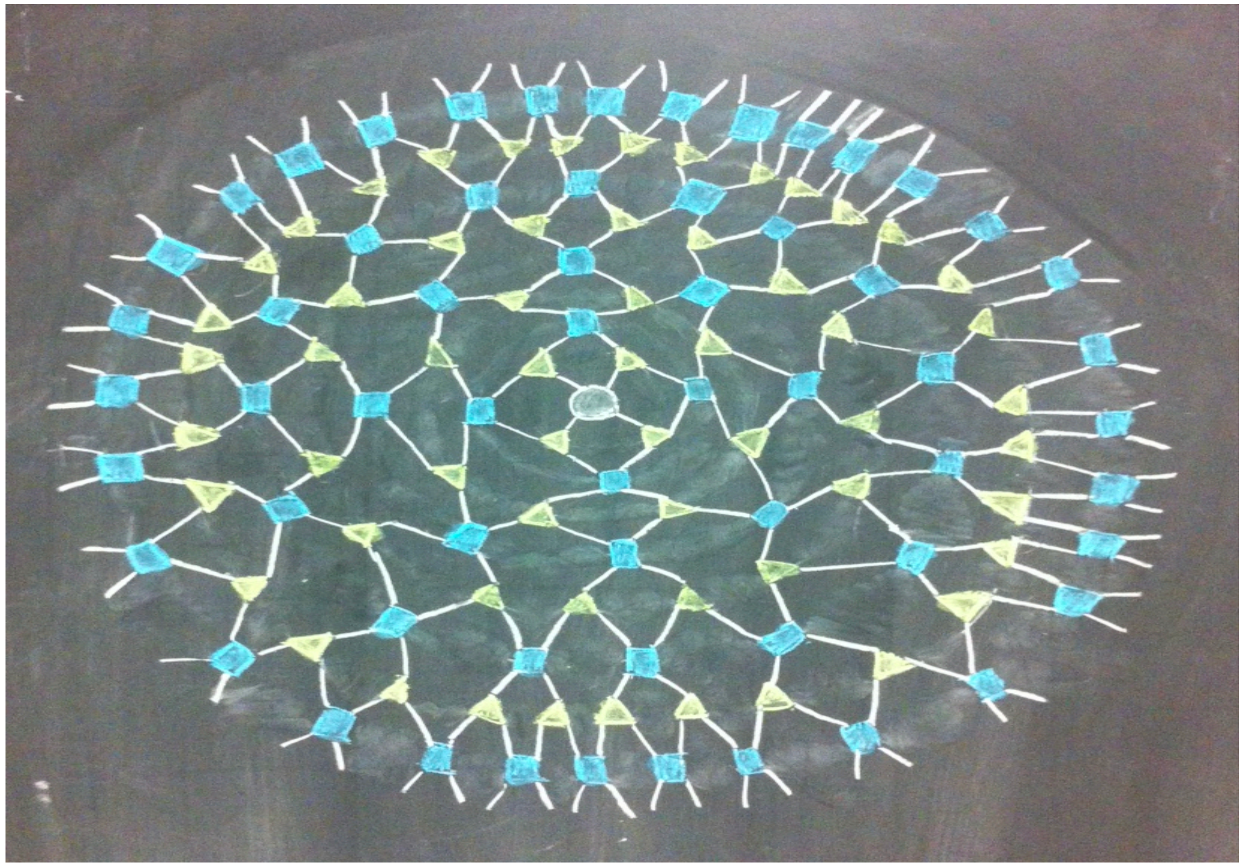
we will eventually learn to think without spacetime, and focus on their nature and origin, rather than taking them for granted

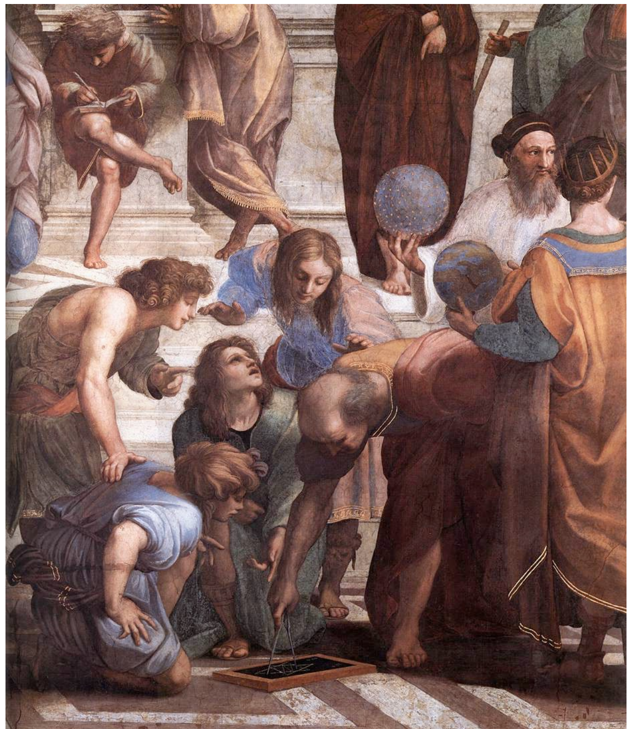
we will get used to the view of the universe as a quantum many-body system, with GR (and Standard Model) as its emergent hydrodynamic-like description

quantum information tools will become routinely used in QG research

we will routinely discuss with our philosophers friends, because we will be thinking at similar open issues







Convergence of approaches

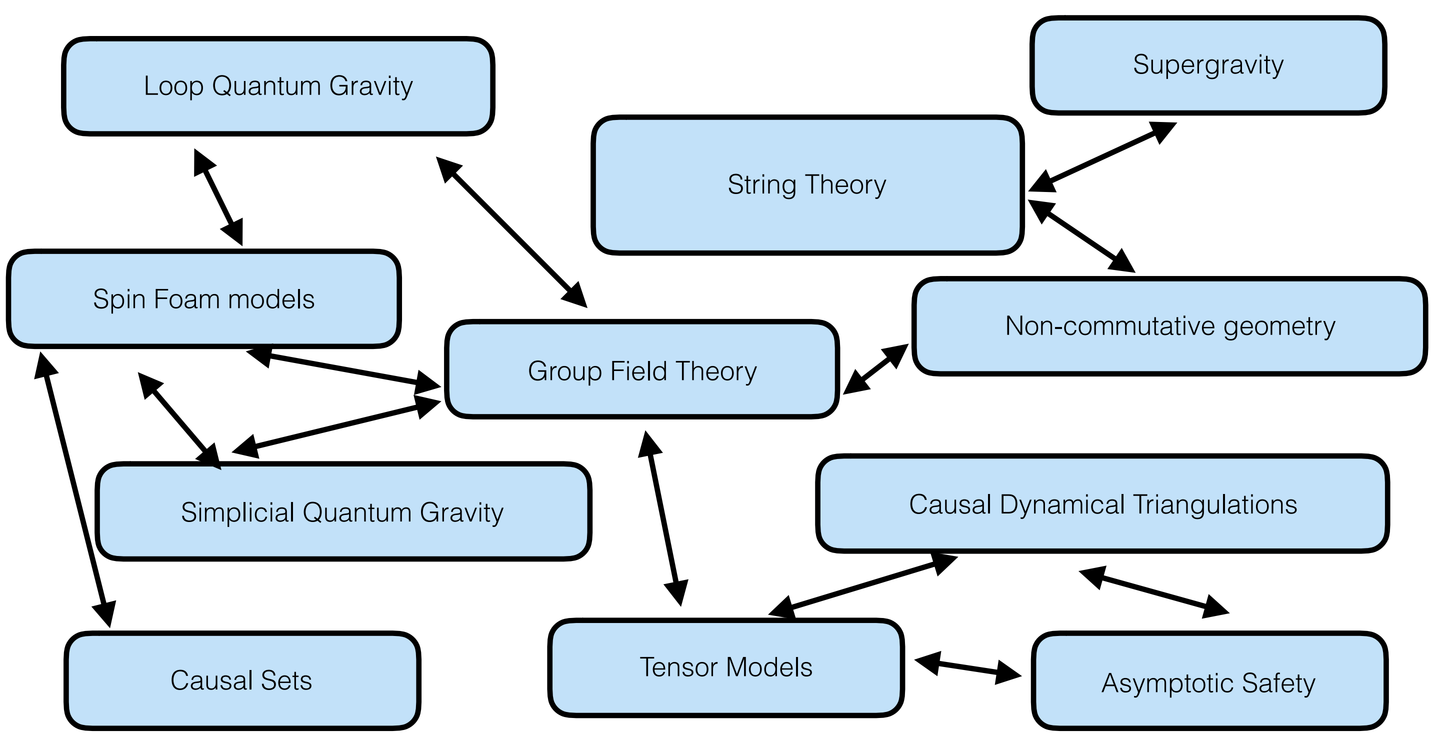
even more solid links between different QG approaches will be discovered

similarities if not equivalence between candidate fundamental structures will be emphasised

some formulations of one approach will be seen as effective descriptions of another

different formalisms will be different available tools for QG physicists, selected according to problem at hand

QG practitioners will focus on common problems, rather than differences in approach, and learn from each other



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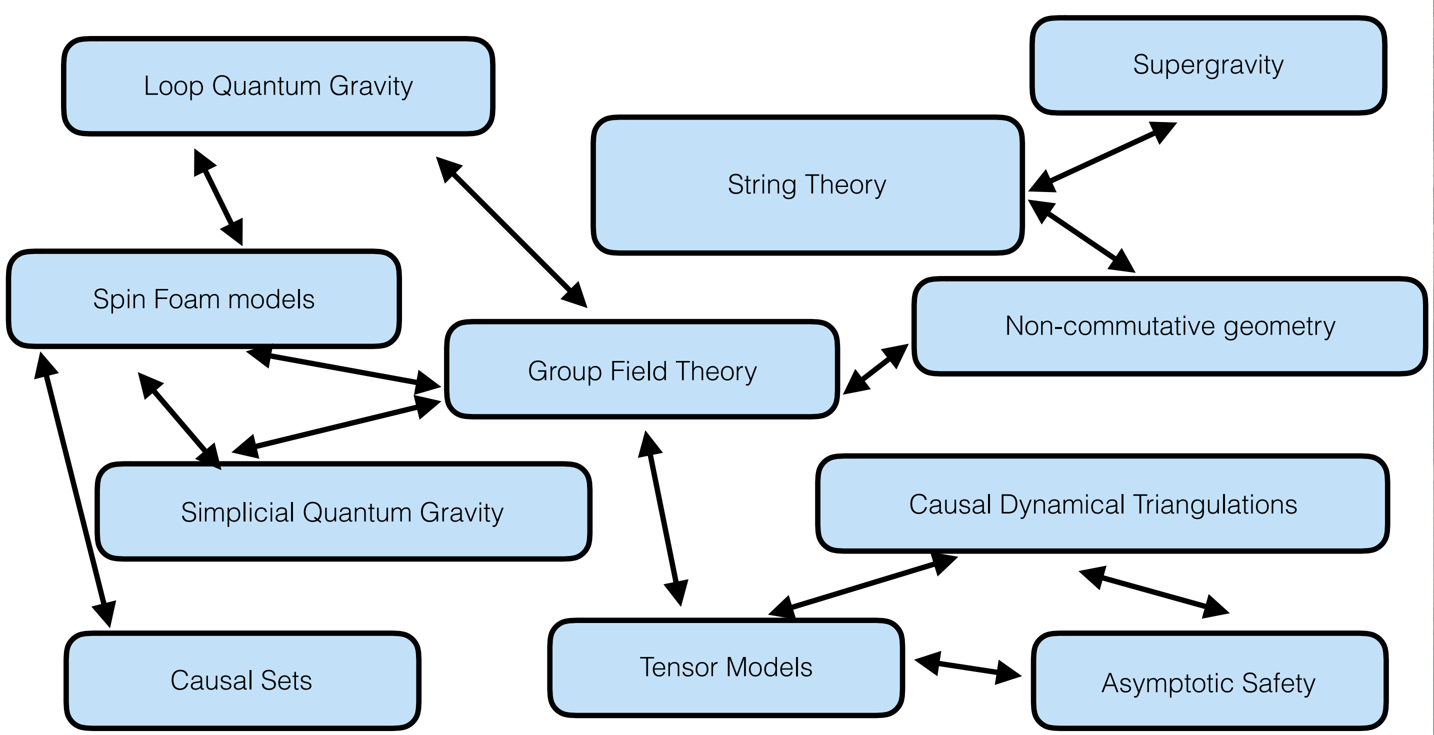
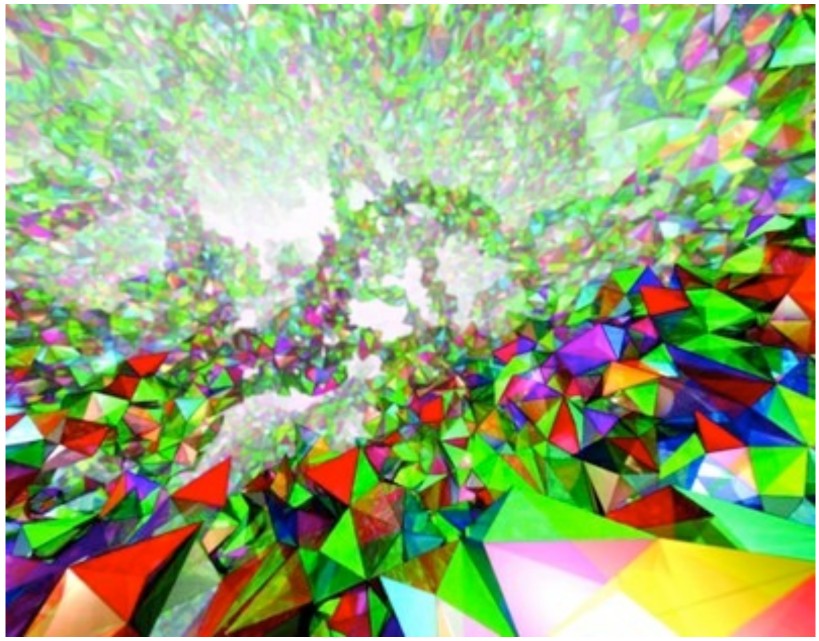


Toward physics, seriously



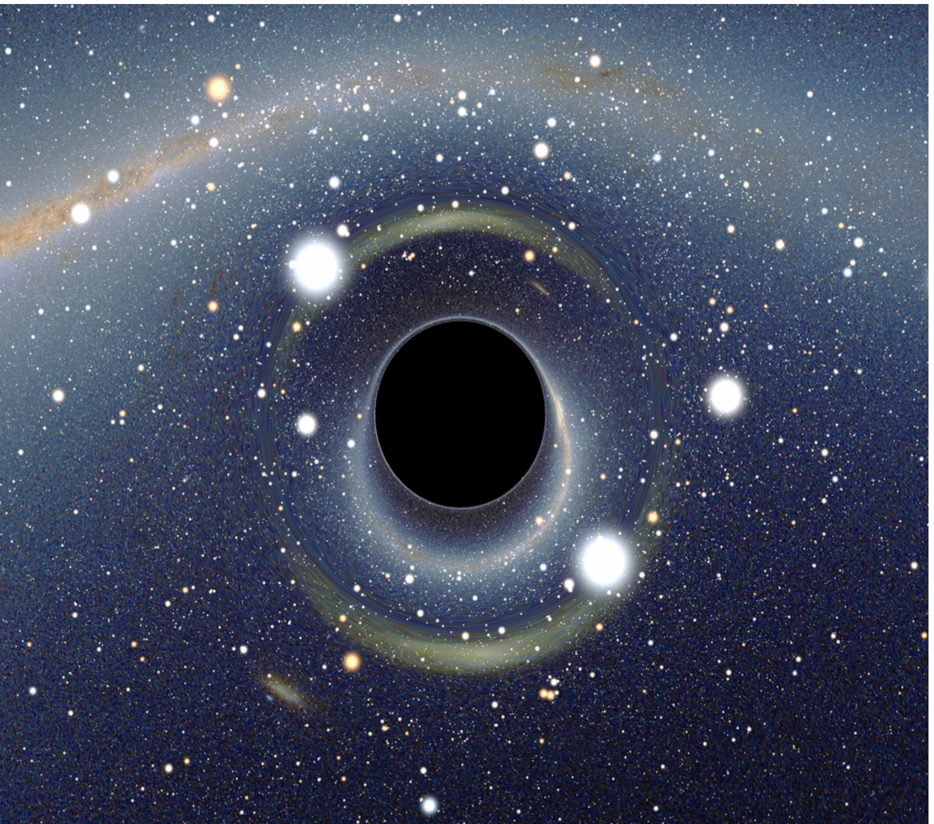
string theorists will focus on identifying fundamental theory

"discrete QG" theorists will focus on extracting effective continuum dynamics

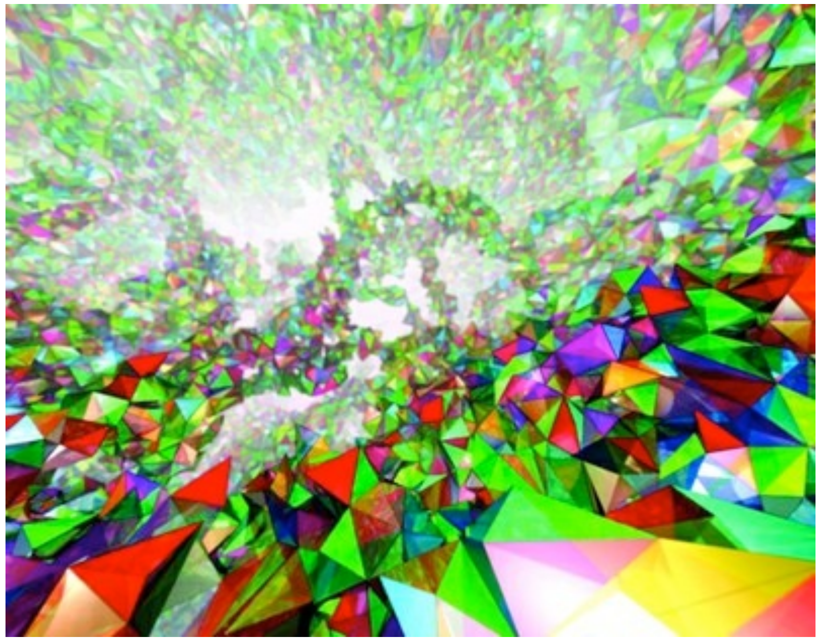
all will focus on QG physics, extracting predictions from full formalisms

we will not look anymore with embarrassment at our experimentalists friends

we will finally know (or at least have solid, full QG proposals) what the universe is made of, how the universe began, what happens to black holes after they evaporate, …..



Toward physics, seriously



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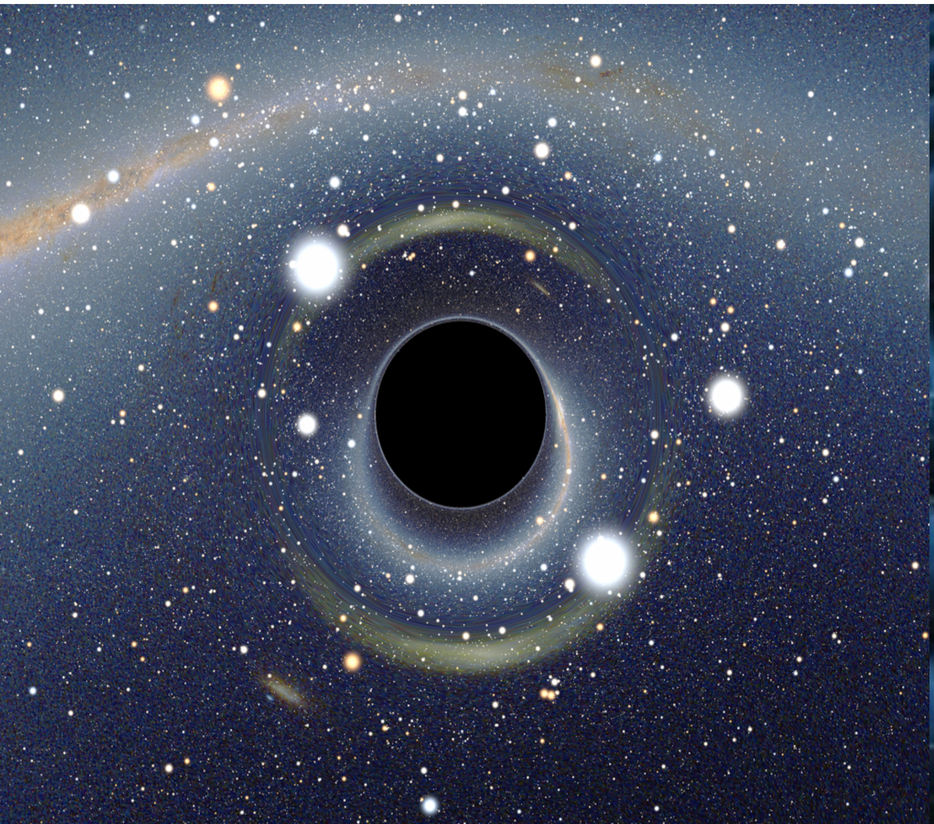

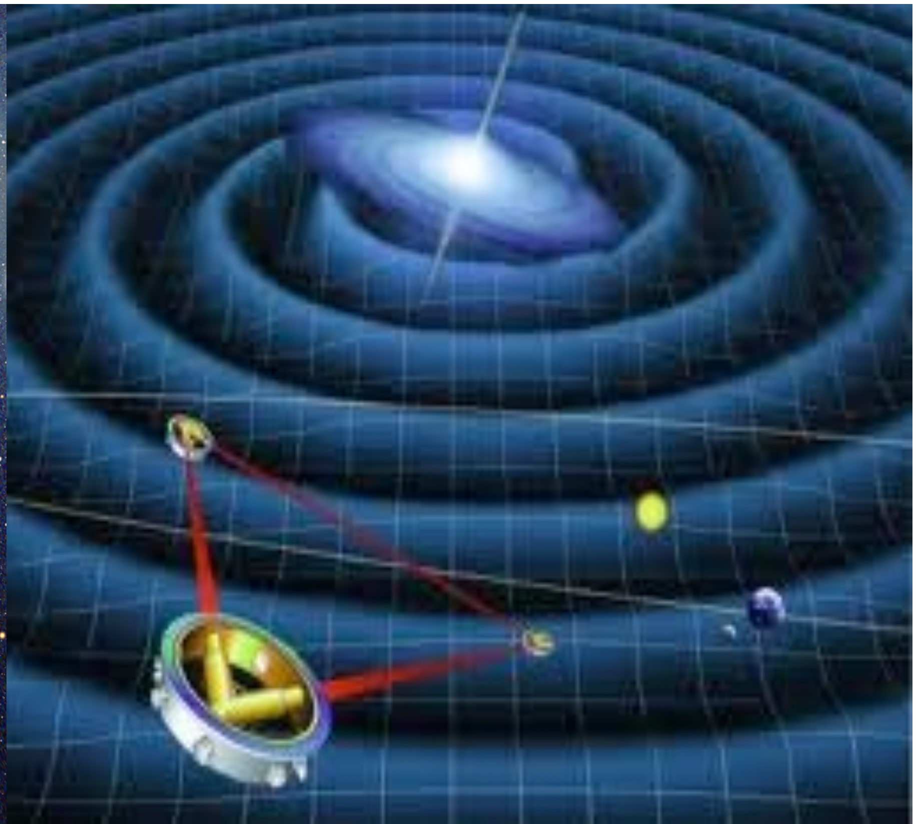

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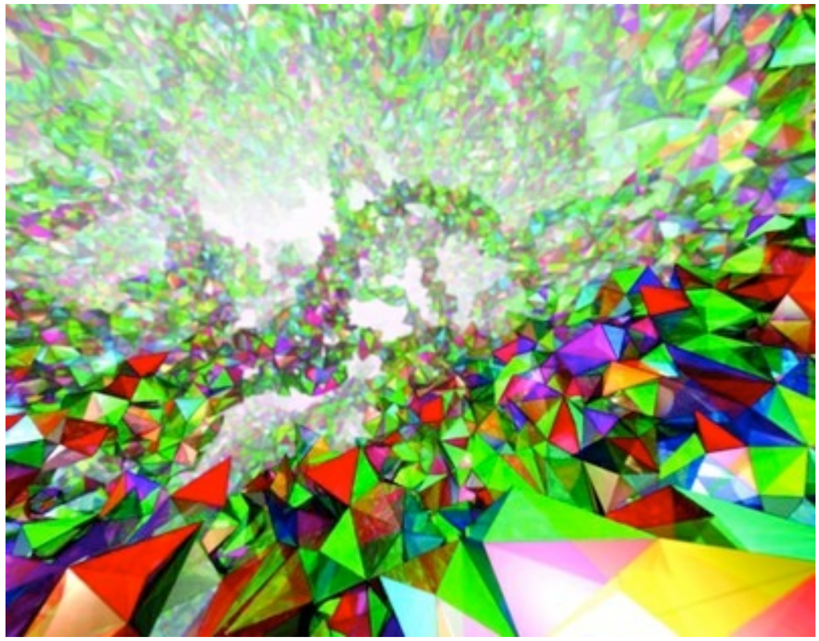

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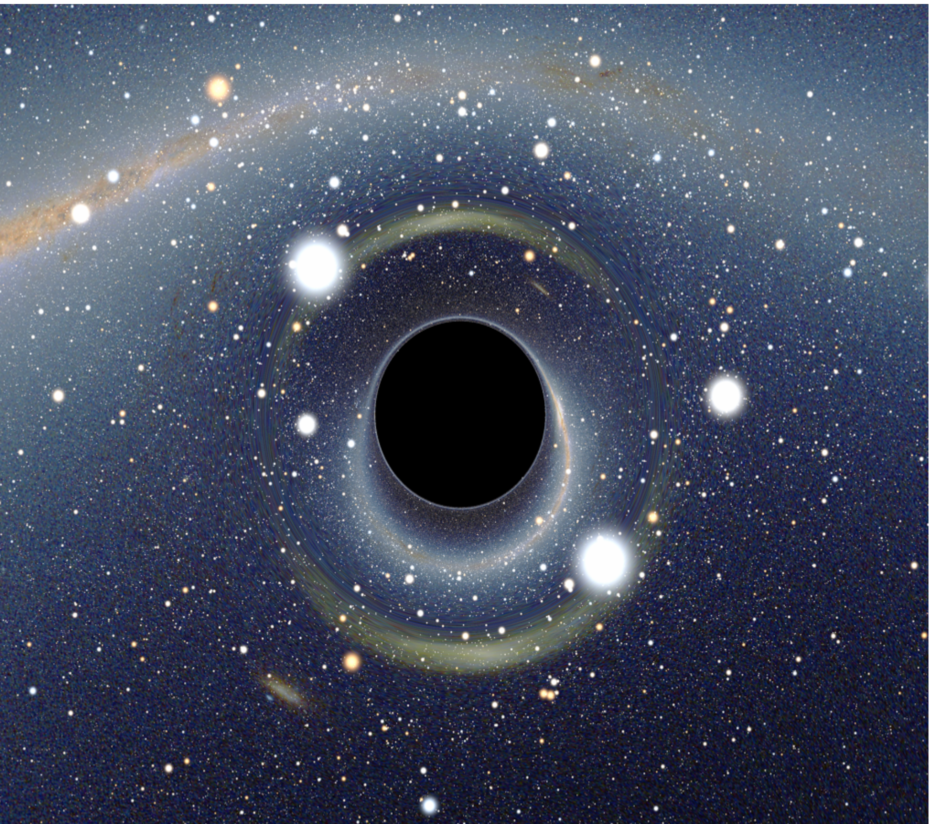

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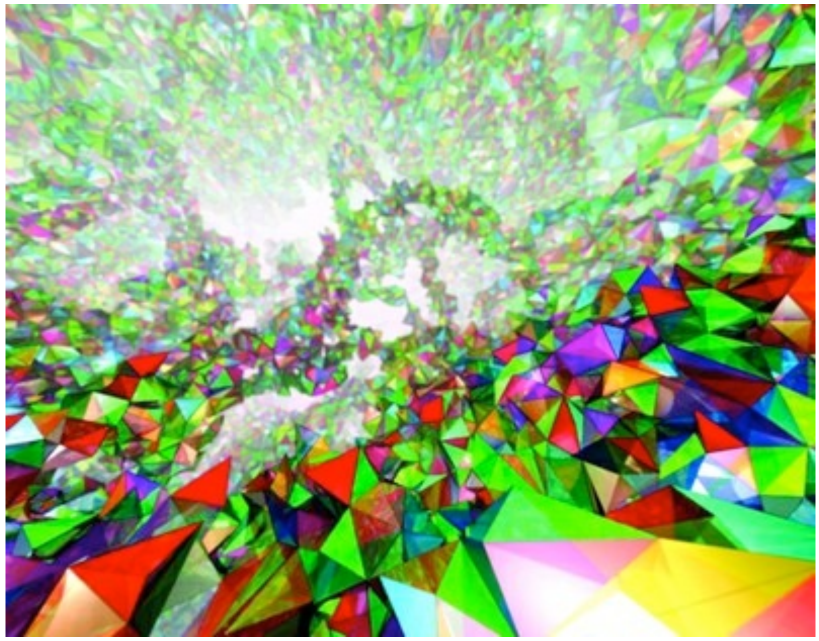

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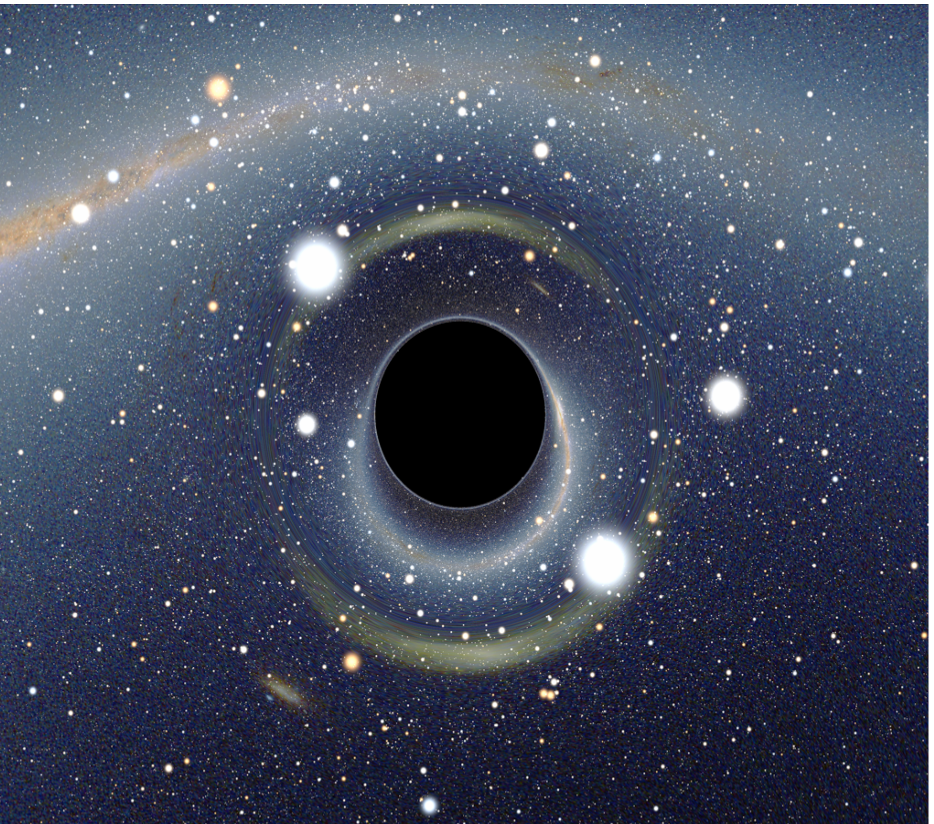

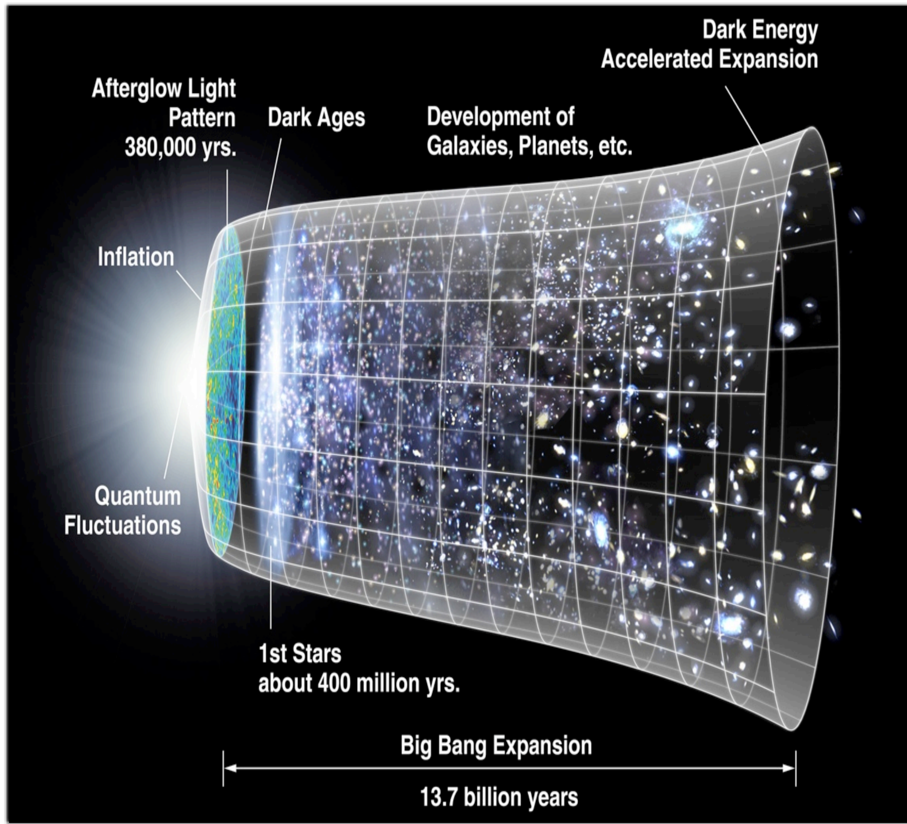

Thank you for your attention!