Forks on the road, on the way to (Loop) Quantum Gravity

Daniele Oriti

Albert Einstein Institute

4th Tux Conference
Tux, Austria
16/02/2016

Fork 1: what is Quantum Gravity?

Quantum Gravity = quantum GR

vs

Quantum Gravity = quantum theory of microstructure of spacetime

a pre-geometric theory with GR as its effective description only

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- only choice of quantisation methods remains
- whatever technical step advances the effort, one takes it
- it implies specific conditions on states, variables, and dynamics, maybe very difficult to impose
- it implies not considering questions and possibilities that could be fostering progress instead

- what is exactly the argument for this direction? being the default option doe snot make it the correct one

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what do we base it on?

how does required continuum effective physics constrain the fundamental theory?

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maybe, quantum GR is only starting strategy, to be pursued as long as there is progress or to learn how BI quantum theories look like …….. fine, but……

very difficult to judge when further progress is not probable and new directions have to be taken

how do we distinguish key insights/results from those that can/should be dismissed?

when and how do we decide that we have learned enough key points, and we can/should use them within a different framework?

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related question: what do we call LQG?

Fork 1b: what are the fundamental structures?

continuum	vs	discrete

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continuum vs discrete

- spacetime manifold assumed
  as background structure

- continuum fields as basic entities
(maybe recast in different form)

- diffeomorphism invariance fundamental

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- spacetime manifold reconstructed from discrete data
  reconstruction both tricky and interesting, could be dynamical
- discrete structures as fundamental entities
(approximated by continuum fields in some regime)
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  approximate symmetry or redundancy in continuum approx.
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in LQG, how we should interpret and treat spin network structures?

- continuum fields ~ cylindrical equivalence:

kinematical or dynamical? feature of all states or of continuum vacuum states only? exact or approximate?

- relevance of combinatorial properties (graph structures)
- construction of Hilbert space

example (IN): Hilbert space of spin networks

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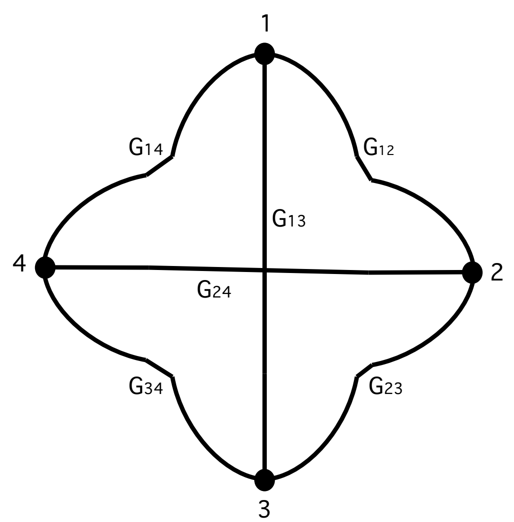
LQG Hilbert space from canonical quantum GR:

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

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



links labelled by j=0 immaterial

equivalence classes of graphs

orthogonality of equivalence classes

space of continuum connection

+ diffeomorphism invariance —-> s-knots

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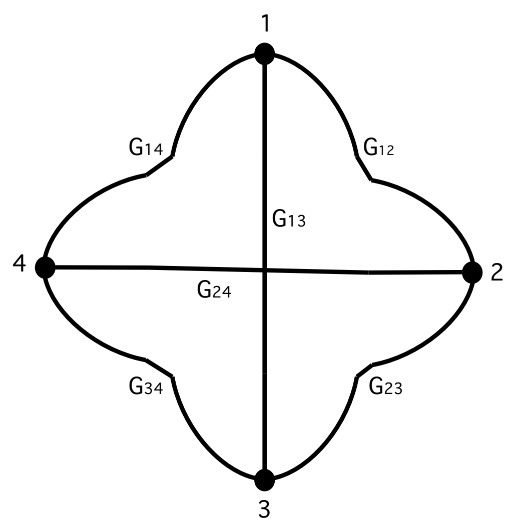

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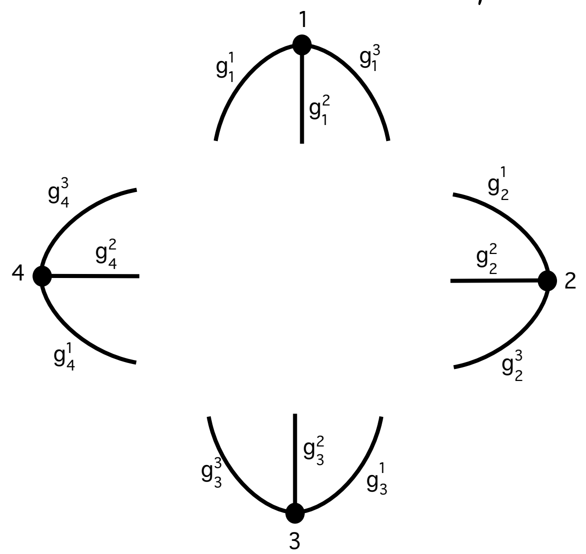
GFT Hilbert space of discrete pre-geometric structures:

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

$$\mathcal{H}_v = L^2\left(G^{\times d}/G\right) \qquad \mathcal{H}_\gamma \subset \mathcal{H}_V$$



no cylindrical equivalence

orthogonality for different #vertices only

no immediate continuum interpretation

no diffeomorphism invariance

no knotting (or other post-embedding info)

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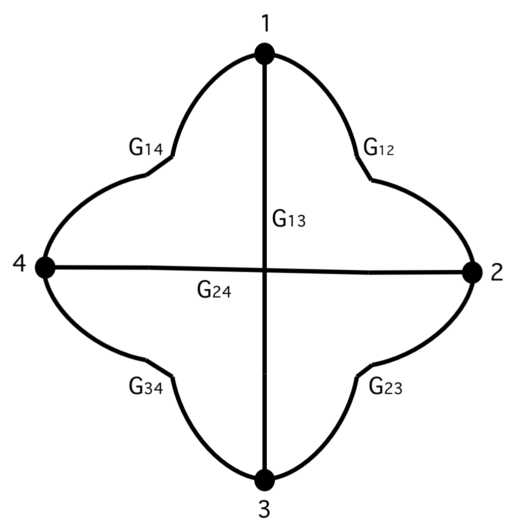

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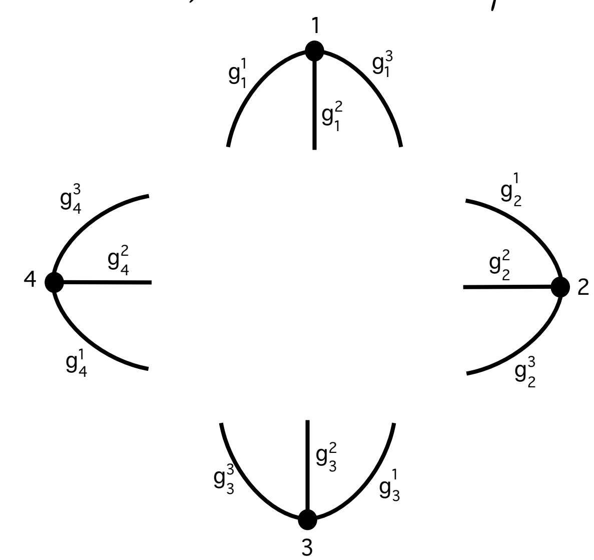

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Spin Foam boundary Hilbert space: GFT one or $\mathcal{H}_1 = \bigoplus_{\gamma} \mathcal{H}_{\gamma}$

other examples where Fork 1 is relevant (IN)

- BF vacuum (Bahr, Dittrich, Geiller, ’14,’15)
- dynamical cylindrical consistency (Dittrich, ‘12)
- SF renormalisation via LGT coarse graining (Bahr, Dittrich, Martin-Benito, Steinhaus, …., ’12,’13,’14)
- GFT condensate reprs (Gielen,DO, Sindoni, Wilson-Ewing, ’13,’14,’15,’16; DO, Tomlin, to appear)
- entanglement in spin networks (Livine, Terno, ’08,’09; Bianchi, ’15; Hamma, Marciano, Zhang,‘15)

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  focus on discrete structures allows easy application of quantum informations tools
  to relate entanglement and geometry for interesting states

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(in 1st order variables, equivalent to SF):

continuum non-trivial in quantum theory (even just dimensionality), albeit under control in classical theory ….

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- entanglement and geometry in AdS/CFT (Swingle, Van Ramsdoonk, ….):

key role of quantum information? explored only if point of view is that continuum geometry is not primitive

connectivity as entanglement, areas as entanglement entropy, distances as relative information, …..

- various guesses at M-theory (Matrix theory, Banks’ holographic spacetime,…):

often surprising similar to structures in LQG/SF/GFT

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topology change before or after continuum approximation?

if after, does it entail degenerate metric or closed time-like loops?

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topology change inbuilt in GFT formulation

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

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from degenerate geometries? how to control it? why does it not proliferate? at odds with cylindrical consistency?

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no projector onto physical states, then

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dominated by spheres in large-N regime

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tensor models $$T^a_{ijk} \;:\; \mathbb{Z}_N^{\times 3} \to \mathbb{C} \qquad a = 0, 1, 2, 3$$

$$S(T) = \frac{1}{2} \sum_{a} \sum_{i,j,k} T^a_{ijk} \bar{T}^a_{ijk} \;-\; \frac{\lambda}{4!\sqrt{N^3}} \sum_{ijklmn} T^0_{ijk} T^1_{klm} T^2_{mjn} T^3_{nli} \quad + \quad c.c.$$

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use techniques from tensor models

dominance of melons in large-cutoff limit (Gurau, '11)

suppression of pseudo-manifolds (Carrozza, DO, '12)

detailed scaling behaviour (Bonzom, Smerlak, '10, '11)

Fork 3: canonical symmetries and causality

canonical projector

vs

“causal” transition amplitude

follows: When the action is written in $3+1$ form [Eqs. (4.2) and (4.4)], a change in the sign of the lapse results in a change in the sign of the action S. Each half-range of the lapse corresponds to a diffeomorphism-invariant sum over geometries. Including both positive and negative lapse is therefore equivalent to first summing $\exp(iS)$ over *geometries* where S is defined with a fixed sign for N and adding it to the corresponding sum over $\exp(-iS)$ over the same class of geometries.

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canonical diffeos "larger" than Lagrangian diffeos (coincide on-shell): can connect positive and negative lapse

lapse vs geometry: +N and -N give the same 4-geometry, but different spacetime orientation

path integral definition of solutions of Hamiltonian constraint (canonical projector):

infinite range of lapse - average over spacetime orientation

$$K[g_{ij}(2),g_{ij}(1)]=\int_{N(x)=-\infty}^{N(x)=\infty}\tilde{K}[2,1,N(\tau_2-\tau_1)]\prod_x d[\ln N(x)(\tau_2-\tau_1)]$$

$$\tilde{K}[2,1;N(\tau_2-\tau_1)]=\int \exp[iS]\prod_{x,\tau}\frac{dg_{ij}(x,\tau)d\pi^{ij}(x,\tau)}{2\pi}$$

Lagrangian (2nd order) counterpart: cosine of EH action

$$K[g_{ij}(2),g_{ij}(1)]=\int e^{i\,S_{EH}}+e^{-\,i\,S_{EH}}=\int cos\,(S_{EH})$$

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path integral definition of "causal" transition amplitude for gravitational states:

semi-infinite range of lapse - definite spacetime orientation

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Langrangian counterpart: standard path integral

$$K_c[g_{ij}(2),g_{ij}(1)]=\int e^{i\,S_{EH}}$$

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set of symmetries slightly larger than Lagrangian diffeos (topological symmetry; coincide on-shell)

independent on spacetime orientation

projector onto solutions of Hamiltonian constraint (F=0)

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projector onto solutions of Hamiltonian constraint (F=0)

4d gravity as constrained BF - constraints do not break orientation independence

$$Z = \int \mathcal{D}B\mathcal{D}A \, \delta\left(C(B)\right) \; e^{i\int_{\mathcal{M}} B\wedge F(A)}$$

cosine of EH action when constraints are imposed, at (half) saddle points (connection on-shell)

$$K[g_{ij}(2), g_{ij}(1)] = \int \; e^{i\,S_{EH}} + e^{-\,i\,S_{EH}} = \int \; cos\left(S_{EH}\right)$$

Fork 3: canonical symmetries and causality

canonical projector vs "causal" transition amplitude

all usual spin foam models (both for BF and for 4d gravity, obtained from constraining BF models):

e.g.

$$Z(\Gamma) = \left(\prod_f \sum_{j_f}\right) \prod_f \Delta_{j_f} \prod_v \left\{ \begin{array}{ccc} j_1 & j_2 & j_3 \\ j_4 & j_5 & j_6 \end{array} \right\}_v$$

amplitudes independent of orientation of 2-complex (simplicial complex)

partial saddle point evaluation (wrt connection only): cosine of Regge action on simplicial complex

$$\left\{ \begin{array}{ccc} j_1 & j_2 & j_3 \\ j_4 & j_5 & j_6 \end{array} \right\}_{v*} \simeq \cos S_R(l_e) \simeq e^{iS_R} + e^{-iS_R}$$

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by basically projecting out unwanted contributions,

can construct "orientation-dependendant" or "causal" spin foam models such that:

- amplitudes are orientation dependent
- partial saddle point evaluation gives exponential of Regge action
- 1-skeleton of underlying 2-complex (in Lorentzian case) has poset structure (with closed time-like loops)
- orientation dependence acquires interpretation of dependence on discrete causal structure

Livine, DO, '02; DO, '05; Engle, '11, '12; Engle, Zipfel, '15

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!!! we know from CDT that causal restrictions may play a crucial role in the emergence of continuum spacetime and from Causal Sets that causal structure is almost all (discrete) geometry

Fork 4: defining and controlling the covariant theory

content with all truncations of a theory

vs

serious about truly defining a theory

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a quantum amplitude for a given spin foam complex (finite # of dof?, which complex?)

the set of all quantum amplitudes for all possible spin foam complexes (no way to compare evaluations)

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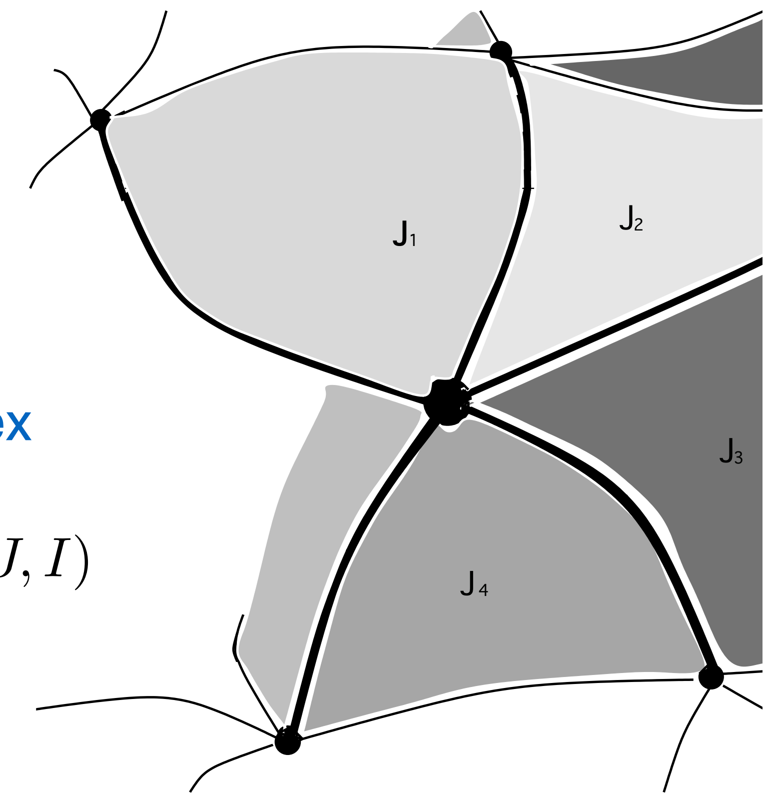
quantum history = spin foam (complex with algebraic data)

need to specify: class of complexes + type of algebraic data



basic element in (definition of) SF model:

quantum amplitude for spin foam —-> quantum amplitude for spin foam complex

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

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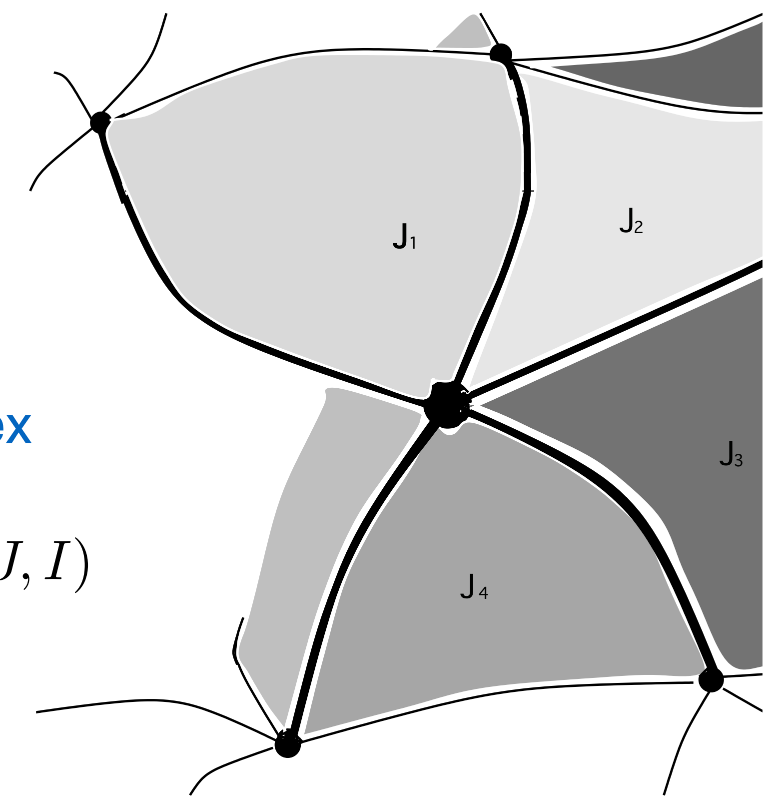

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complete (formal) definition of SF model:

set of all quantum amplitudes for all spin foam complexes (in the chosen class) + organization principle

(for the interacting d.o.f. of the theory)

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directly derived from canonical LQG dynamics? Thiemann, Zipfel, '13

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the GFT proposal: spin foam model with sum over complexes as perturbative expansion of GFT

(can also be derived from “canonical” operator formulation of GFT)

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

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- organizing principle (weights in sum over complexes, partial order in refinement scheme)
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quantum ambiguities in Hamiltonian constraint operator? Perez, ‘07

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in GFT formulation, the issue can be phrased and tackled with standard QFT methods….

GFT perturbative renormalisation

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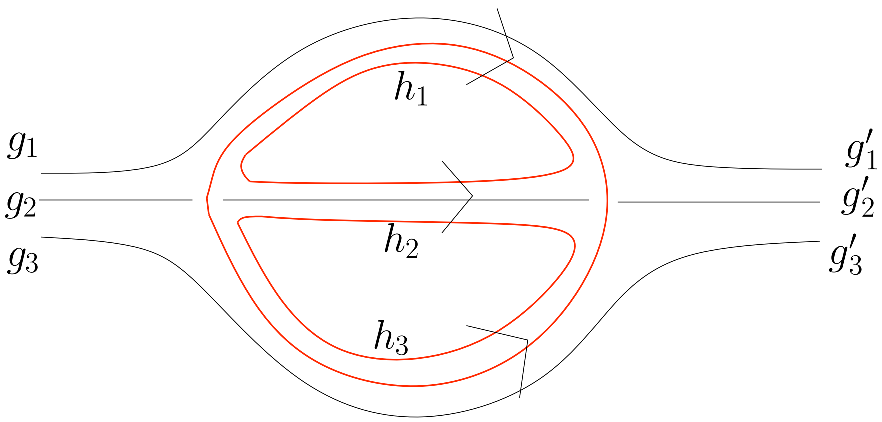

step by step, towards renormalizable 4d gravity models:

- scale indexed by group representations

- interplay between algebraic data and combinatorics of diagrams

- calculation of some radiative corrections T. Krajewski, J. Magnen, V. Rivasseau, A. Tanasa, P. Vitale, '10; A. Riello, '13; Bonzom, Dittrich, '15
- finiteness results in 3d simplicial models (Boulatov with Laplacian kinetic term) Ben Geloun, Bonzom, '11; Ben Geloun, '13

- renormalizable TGFT models (3d, 4d, and higher) - Laplacian + tensorial interactions

Ben Geloun, Rivasseau, '11
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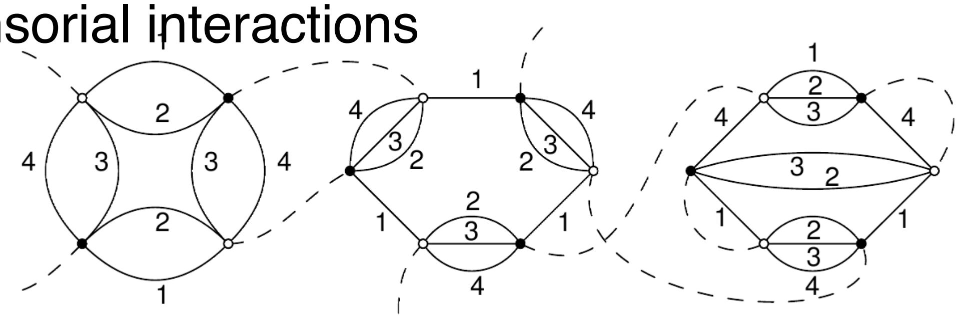
$$S(\varphi,\overline{\varphi}) = \sum_{b\in\mathcal{B}} t_b I_b(\varphi,\overline{\varphi})$$



-> with gauge invariance

—> non-abelian (SU(2))

——> SO(4) or SO(3,1) with simplicity constraints: first results on BC-like 4d models

Lahoche, DO, '15; Carrozza, Lahoche, DO, '16

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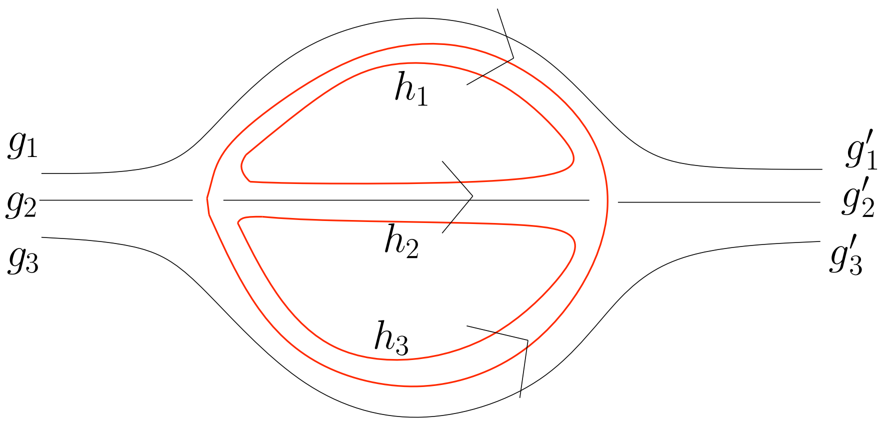
GFT perturbative renormalisation



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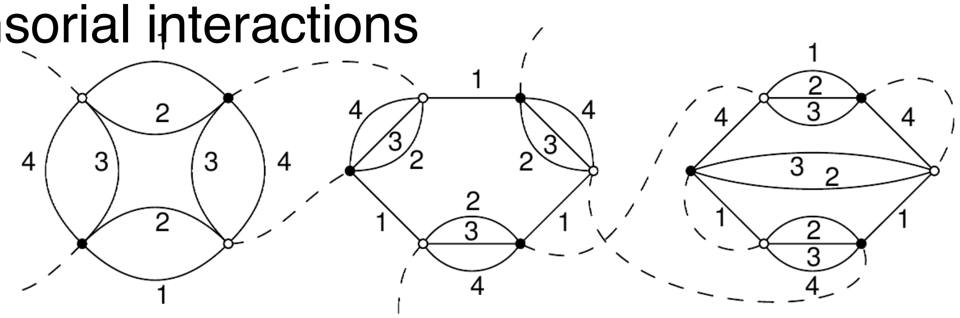

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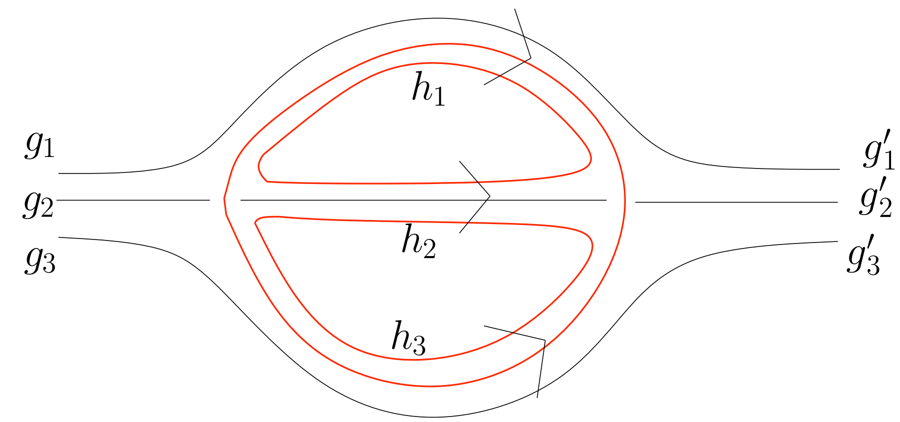

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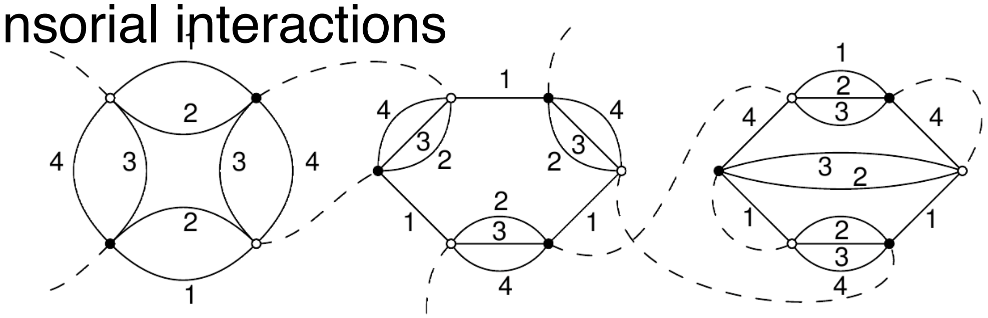

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understand in full the geometric interpretation of UV/IR and of RG flow

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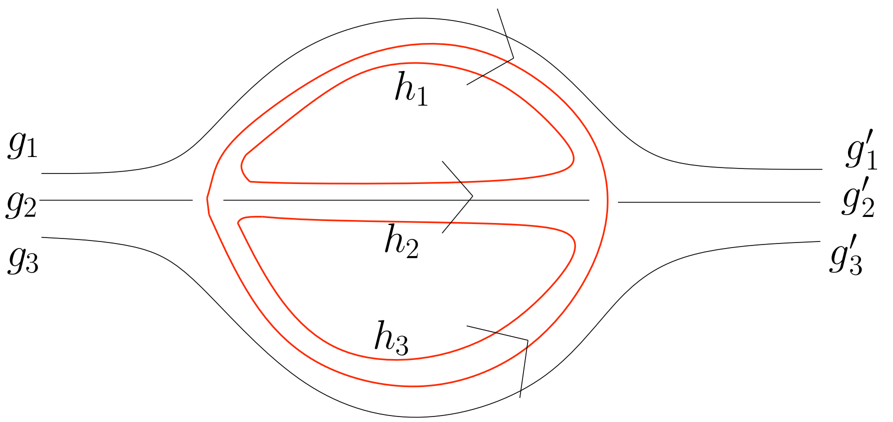

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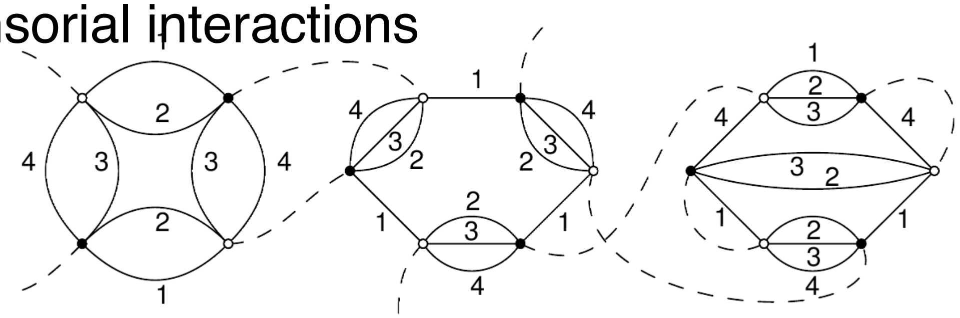

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(what are the phases of LQG?)

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in which one does spacetime emerge?

Koslowski, ’07; DO, ‘07

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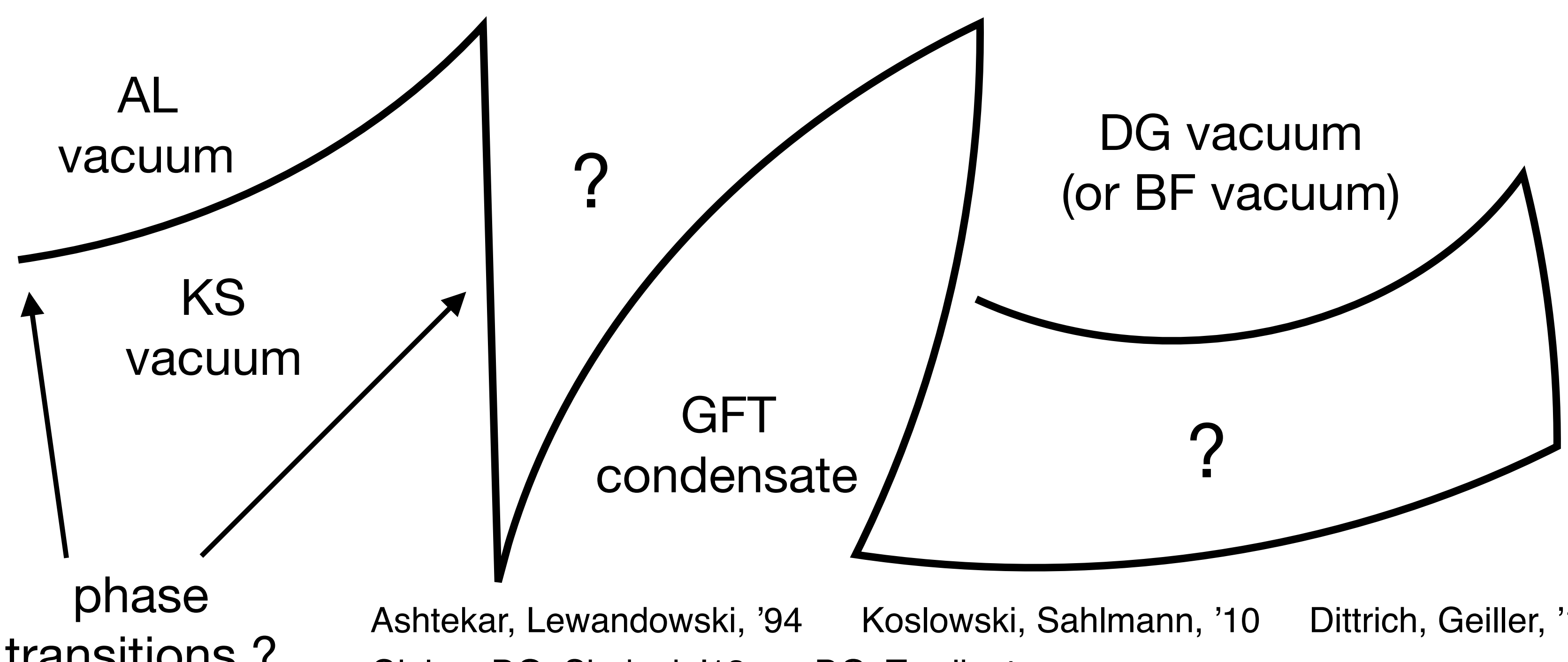

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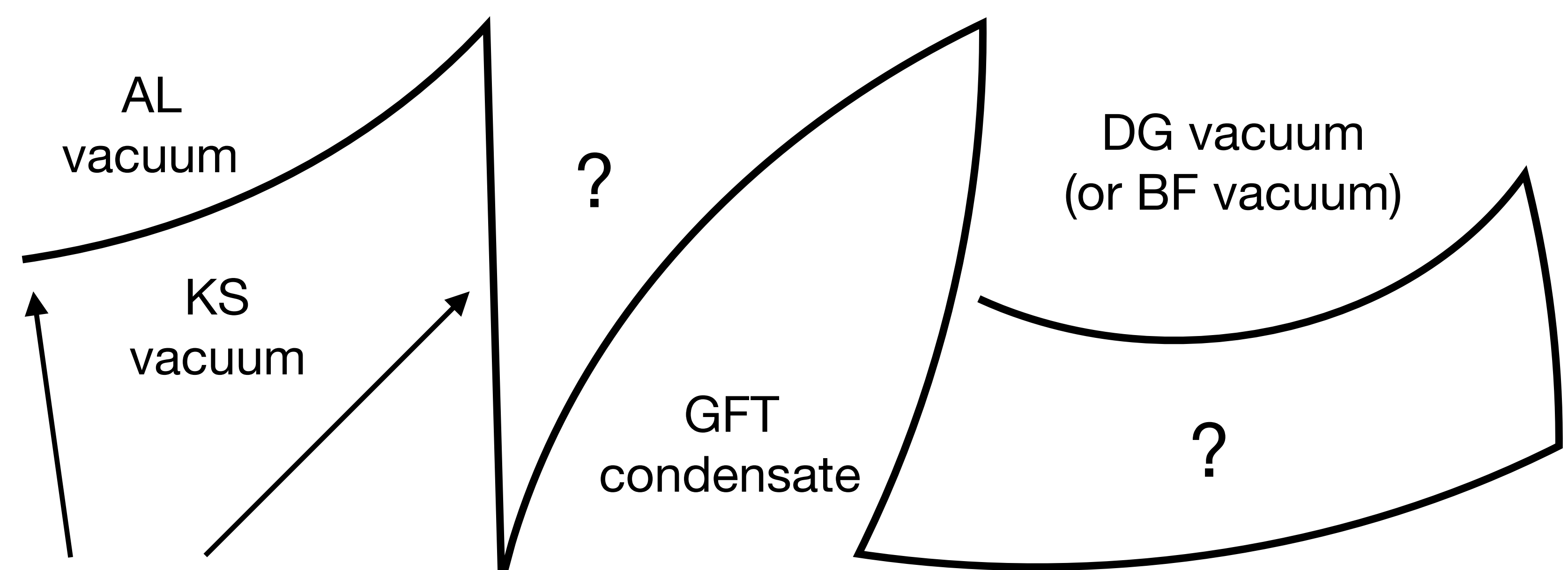
lots of experience and results
in CDT, tensor models



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GFT non-perturbative renormalisation

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

controlling the continuum limit ~ evaluating GFT path integral (in some non-perturbative approximation)

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controlling the continuum limit ~ evaluating GFT path integral (in some non-perturbative approximation)

two directions:

- GFT non-perturbative renormalization and “IR” fixed points (e.g. FRG analysis - e.g. a la Wetterich)

IR fixed point of RG flow of GFT model
IR cutoff N —-> 0
(small J, assuming large-J integrated out)
~ definition of full GFT path integral
~ full continuum limit (all dofs of spin foam model)

$$\mathcal{Z}_N[J] = e^{W_N[J]} = \int_M d\phi\, e^{-S[\phi]-\Delta S_N[\phi]+\mathrm{Tr}_2(J\cdot\phi)}$$

$$\Gamma_N[\varphi] = \sup_J \Big(\mathrm{Tr}_2(J\cdot\varphi) - W_N(J)\Big) - \Delta S_N[\varphi]$$

$$\partial_t \Gamma_N[\varphi] = \frac{1}{2}\overline{\mathrm{Tr}}(\partial_t R_N \cdot [\Gamma_N^{(2)} + R_N]^{-1})$$

- GFT constructive analysis

non-perturbative resummation of perturbative (SF) series

variety of techniques:

- intermediate field method
- loop-vertex expansion
- Borel summability

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recent results:

FRG for (tensorial) GFT models

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Eichhorn, Koslowski, '14

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FRG for (tensorial) GFT models

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- Polchinski formulation based on SD equations — Krajewski, Toriumi, '14 — Eichhorn, Koslowski, '14
- general set-up for Wetterich formulation based on effective action
  - analysis of TGFT on compact U(1)^d — Benedetti, Ben Geloun, DO, '14 ; Ben Geloun, Martini, DO, '15, '16
    - RG flow and phase diagram established
  - analysis of TGFT on non-compact R^d
    - RG flow and phase diagram established
  - analysis of TGFT on non-compact R^d with gauge invariance
    - RG flow and phase diagram established
  - analysis of TGFT on SU(2)^3 — Carrozza, Lahoche, '16

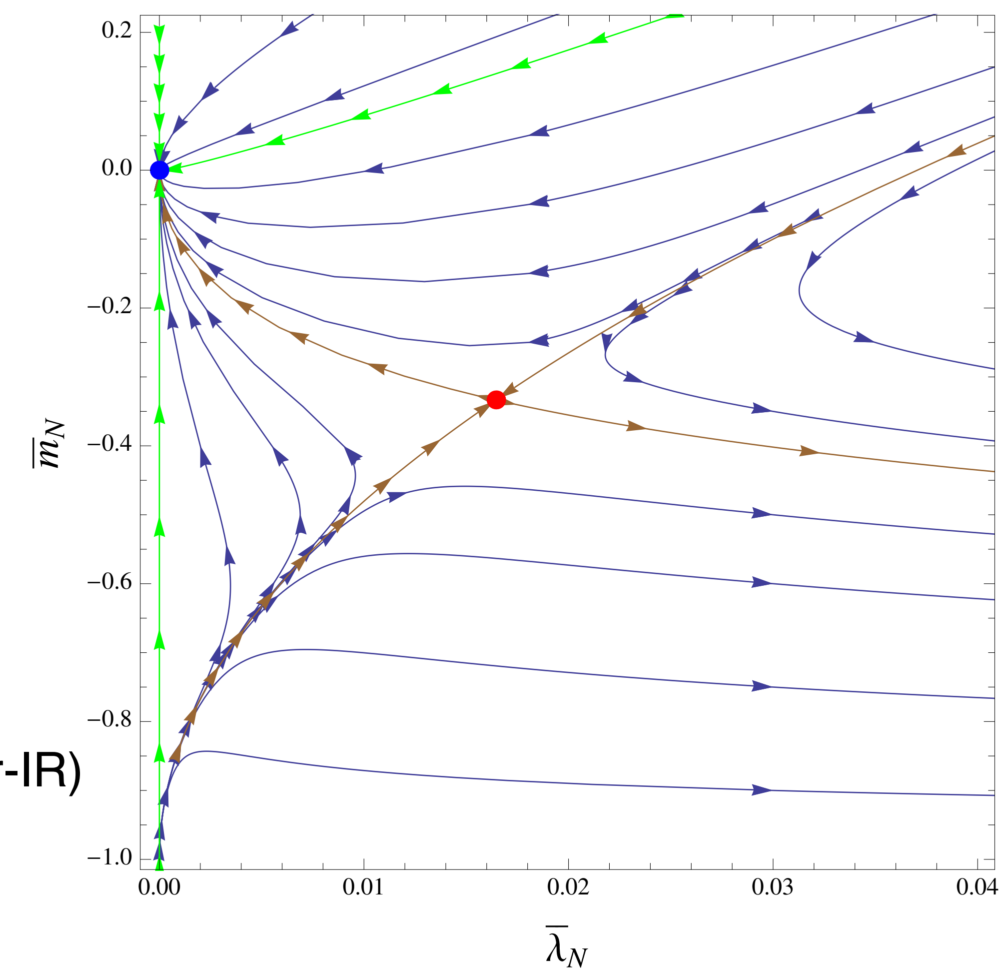
$$
\begin{aligned}
\Gamma_N(\varphi) &= \frac{Z_N}{2}\mathrm{Tr}_2(\varphi\cdot K\cdot\varphi) + \frac{m_N}{2}\mathrm{Tr}_2(\varphi^2) + S^{\mathrm{int}} \\
S'^{\mathrm{int}} &= \frac{\lambda_N}{4}\Big(\mathrm{Tr}_{4;1}(\varphi^4) + \mathrm{Sym}(1\to 2\to 3)\Big) \\
\mathrm{Tr}_2(\varphi\cdot K\cdot\varphi) &= \sum_{p_i\in\mathbb{N}} \varphi_{123}\big(\tfrac{1}{3}\sum_i p_i\big)\varphi_{123} \\
\mathrm{Tr}_2(\varphi^2) &= \sum_{p_i\in\mathbb{N}} \varphi_{123}^2 \\
\mathrm{Tr}_{4;1}(\varphi^4) &= \sum_{p_i,p_i'\in\mathbb{N}} \varphi_{123}\,\varphi_{1'23}\,\varphi_{1'2'3'}\,\varphi_{12'3'}
\end{aligned}
$$

generically (so far):

two FPs (Gaussian-UV, Wilson-Fisher-IR)

one symmetric phase

one broken or condensate phase



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LQG-inspired phenomenological models

vs

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so far, most work of this type

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but how solid? how reliable? how indicative of full theory?

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symmetry reduction vs coarse graining

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if QG = quantum GR

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QFT language of GFT formulation is key tool:

GFT condensate cosmology (Gielen, DO, Sindoni, Wilson-Ewing, ’13,’14,’15,’16)

similar tools: GFT black holes (DO, Pranzetti, Sindoni, ’15,’16)

GFT condensate cosmology

GFT condensates and cosmology as GFT hydrodynamics - LQC embedded (but “transfigured”) in full theory

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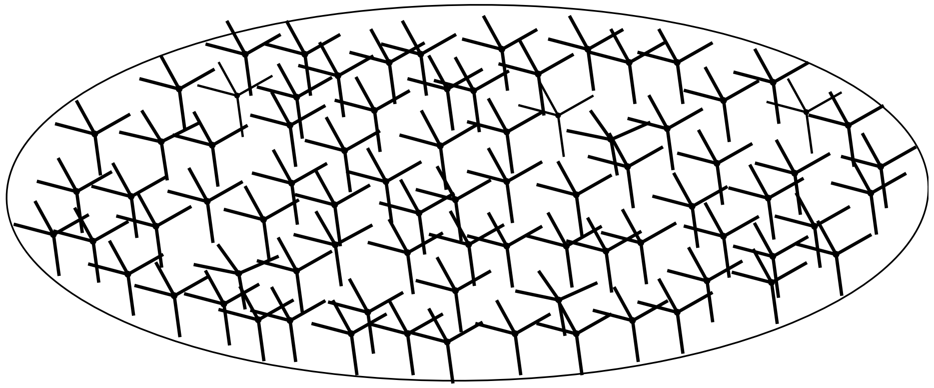
superposition of infinitely many SN dofs



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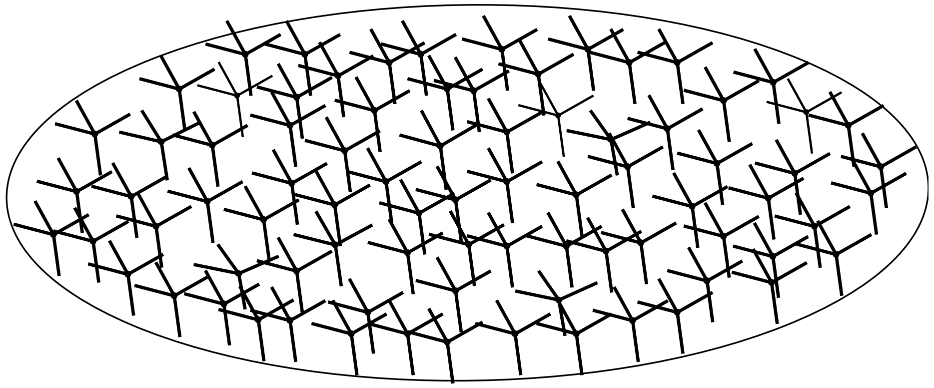

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described by single collective wave function
(depending on homogeneous anisotropic geometric data)

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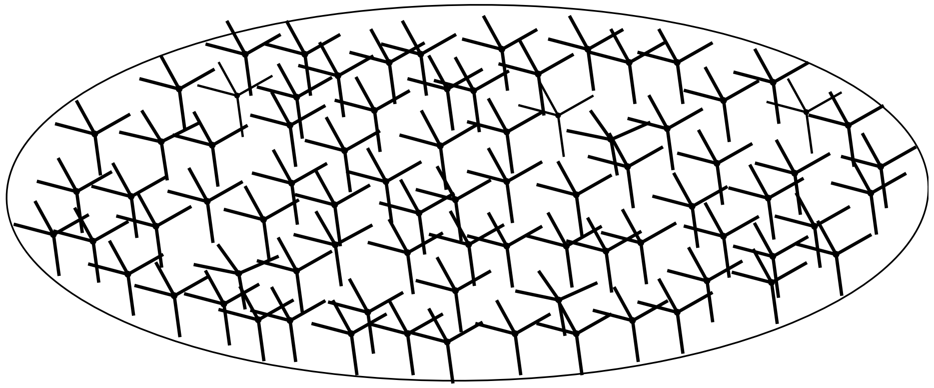

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from SD equations, in simplest truncation

no perturbative (spin foam) expansion - infinite superposition of SF amplitudes

$$0 = \int \mathcal{D}\varphi\,\mathcal{D}\bar{\varphi}\,\frac{\delta}{\delta\bar{\varphi}(g_I)}\left(\mathcal{O}[\varphi,\bar{\varphi}]\,e^{-S[\varphi,\bar{\varphi}]}\right) = \left\langle \frac{\delta\mathcal{O}[\varphi,\bar{\varphi}]}{\delta\bar{\varphi}(g_I)} - \mathcal{O}[\varphi,\bar{\varphi}]\frac{\delta S[\varphi,\bar{\varphi}]}{\delta\bar{\varphi}(g_I)}\right\rangle$$

$$\longrightarrow \quad \int (\mathrm{d}g')^4\ \hat{\mathcal{K}}(g_1,\ldots,g_4,g'_1,\ldots,g'_4)\sigma(g'_1,\ldots,g'_4) + \lambda\,\frac{\delta\mathcal{V}[\varphi,\bar{\varphi}]}{\delta\bar{\varphi}(g_1,\ldots,g_4)}\Big|_{\varphi\to\sigma,\bar{\varphi}\to\bar{\sigma}} = 0$$

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Thank you for your attention!