Alternative Approaches to Quantum Gravity: A Brief Survey

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[with special thanks to Dario Benedetti and Daniele Oriti]

Non-String Quantum Gravity?

A Basic Fact

Perturbative quantum gravity is non-renormalizable

$$\Gamma^{(2)}_{div} = \frac{1}{\varepsilon}\frac{209}{2880}\frac{1}{(16\pi^2)^2}\int dV C_{\mu\nu\rho\sigma}C^{\rho\sigma\lambda\tau}C_{\lambda\tau}{}^{\mu\nu}$$

[Goroff& Sagnotti(1985); van de Ven(1992)]

Two possible conclusions:

- **Consistent quantization of gravity requires a radical modification of Einstein's theory at short distances, in particular inclusion of supersymmetric matter; or**
- **UV divergences are artefacts of perturbative treatment $\Rightarrow$ disappear upon a proper *non-perturbative* quantization of Einstein's theory.**

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The real problem (also for non-perturbative approaches): infinitely many ambiguities and loss of predictivity!

MAIN QUESTION: can properly quantized GR 'stand on its own feet' as a quantum theory of gravity?

Thus: is there an alternative to the particle physics stratagem of looking for mechanisms to cancel or remove the UV infinities of perturbatively quantized gravity by introducing a whole *überbau* of extra dimensions, supersymmetry, relativistic extended objects, infinite towers of massive string states, D-branes, *etc.*? And is it enough to stick with basic features of GR, to wit:

- **General Covariance**
- **Background Independence**
- $D = 4$ **space-time dimensions**

in order to arrive at a quantization of geometry and space-time?

??????

(Partial) List of Alternative Approaches

- Canonical quantization in metric formalism
- Path integrals: Euclidean, Lorentzian, matrix models,...
- Loop Quantum Gravity (LQG)
- Discrete Quantum Gravity: Regge calculus
- Discrete Quantum Gravity: Causal Dynamical Triangulations
- Discrete Quantum Gravity: spin foams, group field theory
- Non-commutative geometry and non-commutative space-time
- Asymptotic Safety and RG Fixed Points
- Emergent (Quantum) Gravity
- Causal Sets
- Cellular Automata ('computing quantum space-time'), ...

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A (very incomplete) list of reviews

1. C. Kiefer, *Quantum Gravity*, C.U.P. (2012)
2. A. Ashtekar and J. Lewandowski, CQG 21 (2004) R53
3. C. Rovelli, *Quantum Gravity*, C.U.P. (2004)
4. T. Thiemann, *Modern canonical quantum general relativity*, C.U.P. (2007)
5. J. Baez, *Spin Foam Models*, CQG 15(1998)1827
6. A. Perez, *The spin foam approach to quantum gravity*, `arXiv:1205.2019`
7. D. Oriti, `arXiv:1110.5606`
8. V. Rivasseau, *The tensor track*, talk at AEI (10 July 2012)
9. M. Reuter and F. Saueressig, *Quantum Einstein Gravity*, New J. Phys. 14 (2012) 055022
10. A. Ambjorn, A. Goehrlich, J. Jurkiewicz and R. Loll, *Non-perturbative Quantum Gravity*, `arXiv:1203.3591`
11. HN, K. Peeters and M. Zamaklar, CQG22(2005)R193
12. S. Alexandrov and P. Roche, `arXiv:1009.4475`

Asymptotic Safety (I)

[Weinberg(1979), Reuter(1995), Percacci(2006), Niedermaier(2007), Reuter&Saueressig(2012)]

- **Approach is closest in spirit to conventional QFT ideas (RG flow, RG group, etc.** [Wilson, Kadanoff,...]**)**
- **If any of the non-perturbative approaches 'succeeds' the description of resulting low energy theory via an *effective action* will probably reduce to this!**
- **Approach pretends to be *agnostic about microscopic theory*, relevant information is in universality classes.**
- M_{Planck} **is analogous to** Λ_{QCD}: ***lower end* of asymptotic scaling regime** $\Rightarrow$ **observable effects only if some prediction can be made about IR limit as theory flows down from asymptotically safe fixed point.**

Asymptotic Safety (II): basic assumptions

- **The UV limit of gravity is determined by a non-Gaussian fixed point (NGFP) of the gravitational renormalization group (RG) flow which controls the behavior of theory at high energies and renders physical quantities safe from unphysical divergences.**

- **The NGFP belongs to a UV critical hypersurface *of finite dimension* within the ∞-dimensional space of *essential couplings* (a coupling is called 'essential' if it cannot be absorbed into a field redefinition).**

- **Aim: construct scale dependent effective action Γ_k**

$$\lim_{k \to \infty} \Gamma_k = \text{bare action} \;, \quad \lim_{k \to 0} \Gamma_k = \text{effective low energy action}$$

- **Dynamical information about the theory is not in the flow equation, but in its *initial condition*.**

Functional RG Equation

[Wegner&Houghton(1973), Polchinski(1984), Wetterich(1993), Reuter(1998)]

Effective action $\Gamma_{k,\Lambda}$ **for gravity (with UV cutoff Λ) obeys FRGE**

$$k\partial_k \Gamma_{k,\Lambda}[\bar{g}, h, \dots] = \frac{1}{2}\,\mathrm{Tr}\left[\left(\frac{\delta^2\Gamma_{k,\Lambda}[\bar{g}, h, \dots]}{\delta h\,\delta h} + \mathcal{R}_k\right)^{-1} k\partial_k \mathcal{R}_k\right]$$

with $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$ **,** $(\dots)$ **= everything else (matter, ghosts,...)**

- **UV cutoff limit** $\lim_{\Lambda\to\infty}\Gamma_{k,\Lambda} = \Gamma_{k,\infty} \equiv \Gamma_k$ ***is assumed*** **to exist.**
- **Background covariance:** $\delta\bar{g}_{\mu\nu} = 2\bar{D}_{(\mu}\xi_{\nu)}$, $\delta h_{\mu\nu} = \xi^\rho \bar{D}_\rho h_{\mu\nu} + 2\bar{D}_{(\mu}\xi^\rho h_{\nu)\rho}$
- $\mathcal{R}_k$ **= cutoff function to 'integrate out' modes with** $k < \mu < \Lambda$

$$\Gamma_k = \tilde{\Gamma}_k - \Delta_k S \quad , \quad \Delta_k S \propto \int d^d x \sqrt{\bar{g}}\, h_{\mu\nu}\, \mathcal{R}_k^{\mu\nu|\rho\sigma}[\bar{g}]\, h_{\rho\sigma}$$

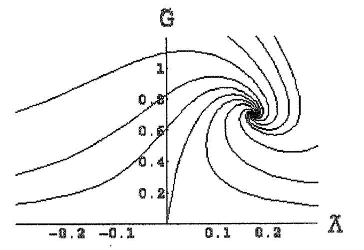
Thus: cutoff scale is 'measured' w.r.t. background metric $\bar{g}$.

- **Final effective action for gravity:** $\Gamma_k[g] := \Gamma_k[g, h=0]$
- $\Gamma_k[g]$ **by itself does *not* (and cannot?) obey a covariant FRGE.**
- **Scale-dependent metric** $\langle g_{\mu\nu}\rangle_k$ **from** $\delta\Gamma_k[g]/\delta g\big|_{g_{\mu\nu}=\langle g_{\mu\nu}\rangle_k} = 0$**.**

Circumstantial Evidence

To analyze FRGE truncate to *finite dimensional subspace* of couplings: $\tilde{\Gamma}_k[\bar{g}, h, \ldots] \approx \sum_{j=1}^{n} u_j(k) P_j[\bar{g}, h, \ldots]$, substitute ansatz into FRGE and truncate again $\rightarrow$

NGFP's are found to exist for $P_j[g] \sim \Lambda\,,\ R^1\,,\ \ldots\,,\ R^8\,,$ $C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}$, and various matter couplings.



the flow of the dimensionless cosmological constant and Newton constant in the Einstein-Hilbert truncation.

- **UV critical surface *remains 3-dimensional* for $\sum R^n\,,\ n \leq 8$.**
- **NGFP's exist also for matter couplings and for $D > 4$.**
- **Essentially no particular structure of matter sector required.**
- **Still to be done: two-loop counterterm $\Gamma^{(2)}_{div}$ (the acid test?).**

Open issues

- **No general argument in sight for existence and stability of NGFP in ∞-dimensional space of couplings.**
- **Unitarity of R^n theories and absence of ghosts?**
- **BRST invariance requires $\Gamma_k[\bar{g}, h, ...] = \Gamma_k[\bar{g} + h, ...]$.**
- **Role of field redefinitions $\Leftrightarrow$ 'covariance in field space'?**

  [Vilkovisky(1984); Branchina,Meissner,Veneziano(2003)]
- **Link to other approaches: effective reduction to $D = 2$ at short distances is also seen by CDT.**
- **Resolution of space-time singularities in GR? Presumably(?): $\langle g_{\mu\nu} \rangle_k$ non-singular for $k \to \infty \Rightarrow$ Does space-time remain a continuum below ℓ_{Planck}?**

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- **A question aside: If $N = 8$ supergravity is *not* finite could it be asymptotically safe?**

Canonical Quantization

Non-perturbative and background independent approach: quantum metric fluctuations and quantum geometry.

- **Hamiltonian approach: manifest space-time covariance is lost through split ('foliation') of space-time as $\mathcal{M} = \Sigma \times \mathbb{R}$.**
- **$\rightarrow$ Space-time geometry is viewed as the *evolution of spatial geometry in time* according to Einstein's equations.**
- **Geometrodynamics: canonical *dynamical* degrees of freedom**

$$g_{mn}(t, \mathbf{x}) \quad \textbf{and} \quad \Pi^{mn}(t, \mathbf{x}) = \frac{\delta \mathcal{S}_{\text{Einstein}}}{\delta \dot{g}_{mn}(t, \mathbf{x})}$$

- **Dynamics defined by *constraints* (via shift and lapse): Hamiltonian constraint $\mathcal{H}(\mathbf{x})$ and diffeomorphism constraints $\mathcal{D}_m(\mathbf{x})$**
- **Quantum Constraint Algebra from classical Poisson algebra:**

$$\{\mathcal{D}, \mathcal{D}\} \sim \mathcal{D} \qquad \{\mathcal{D}, \mathcal{H}\} \sim \mathcal{H} \qquad \{\mathcal{H}, \mathcal{H}\} \sim \mathcal{D} \ ,$$

possibly modulo anomalies (cf. Witt vs. Virasoro algebra).
$\Rightarrow$ Quantum space-time covariance must be proven!

New Variables, New Perspectives?

- **New canonical variables: replace g_{mn} by connection**

$$A_m{}^a = -\frac{1}{2}\epsilon^{abc}\omega_{m\,bc} + \gamma K_m{}^a$$

[$\omega_{m\,bc}$ = spatial spin connection, $K_m{}^a$ = extrinsic curvature]

- **New canonical brackets** [Ashtekar (1986)]

$$\begin{aligned} \{A_m{}^a(\mathbf{x}), E_b{}^n(\mathbf{y})\} &= \gamma\delta_b^a\delta_m^n\delta^{(3)}(\mathbf{x},\mathbf{y}) \ , \\ \{A_m{}^a(\mathbf{x}), A_n{}^b(\mathbf{y})\} &= \{E_a{}^m(\mathbf{x}), E_b{}^n(\mathbf{y})\} = 0 \end{aligned}$$

with conjugate variable $E_a{}^m$ = inverse densitized dreibein
$\Rightarrow$ for $\gamma = \pm i$ constraints become polynomial

$$E_a{}^n F_{mn}{}^a(A) \approx 0 \ , \quad \epsilon^{abc} E_a{}^m E_b{}^n F_{mn\,c}(A) \approx 0 \ , \quad D_m(A) E_a{}^m \approx 0$$

with $SU(2)$ field strength $F_{mna} \equiv \partial_m A_{na} - \partial_n A_{ma} + \varepsilon_{abc} A_m{}^b A_n{}^c$.

- **But reality constraint difficult to elevate to quantum theory $\rightarrow \gamma$ is nowadays taken real ('Barbero-Immirzi parameter')**

Loop Quantum Gravity (LQG)

- **Modern canonical variables: holonomy (along edge e)**

$$h_e[A] = \mathcal{P} \exp \int_e A$$

- **Conjugate variable = flux through area element S**

$$F_S^a[E] := \int_S dF^a = \int_S \epsilon_{mnp} E_a{}^m dx^n \wedge dx^p$$

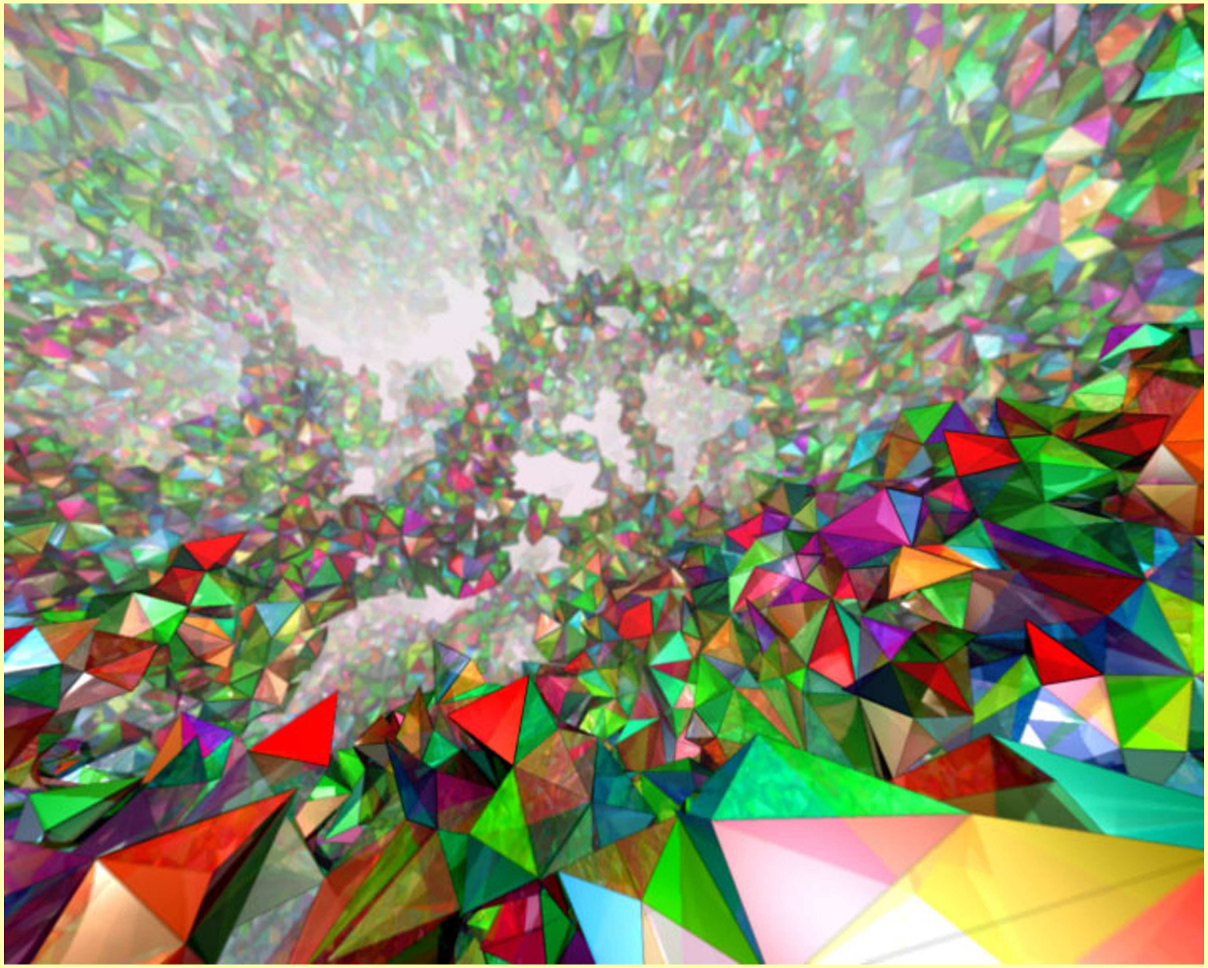
- **act on wave functionals $\Psi_{\{\Gamma,C\}}[A] = f_C(h_{e_1}[A], \ldots, h_{e_n}[A])$ with *spin network* Γ (graph consisting of *edges* e and *vertices* v).**

- **New feature: Kinematical Hilbert space $\mathcal{H}_{kin}$ can be defined, but is *non-separable* $\Rightarrow$ operators not weakly continuous.**
  Cf. ordinary quantum mechanics: replace $\langle x|x'\rangle = \delta(x - x')$ *by* $\langle x|x'\rangle = 1$ *if* $x = x'$ *and* $= 0$ *if* $x \neq x'$ $\rightarrow$ *'pulverize' real line!*

- **$\Rightarrow$ No UV divergences (and thus no anomalies) ?**

- **$\Rightarrow$ No negative norm states ?** [cf. Narnhofer&Thirring (1992)]

Quantum Geometry according to LQG



Status of Hamiltonian constraint

- **Diffeomorphism constraint solved formally:** $\mathcal{X}_\Gamma = \sum_{\phi\in\mathrm{Diff}} \Psi_{\Gamma\circ\phi}$
- $\Rightarrow$ **Hamiltonian constraint not defined on $\mathcal{H}_{kin}$, but on distribution space $\mathcal{S}$ ('habitat') = dual of dense subspace $\subset \mathcal{H}_{kin}$.**
- **Main success: definition of regulated Hamiltonian (with $\epsilon > 0$) by means of kinematical operators (volume, etc.)** [Thiemann(2000)]

$$\hat{H}[N,\epsilon] \;=\; \sum_\alpha N(v_\alpha)\,\epsilon^{mnp}\mathrm{Tr}\big((h_{\partial P_{mn}(\epsilon)} - h^{-1}_{\partial P_{mn}(\epsilon)})\,h_p^{-1}\,[h_p, V]\big)$$
$$+\frac{1}{2}(1+\gamma^2)\sum_\alpha N(v_\alpha)\,\epsilon^{mnp}\mathrm{Tr}\big(h_m^{-1}\,[h_m,\bar{K}]\,h_n^{-1}\,[h_n,\bar{K}]\,h_p^{-1}[h_p,V]\big)$$

- **Proper definition relies on diffeomeorphism invariance of states $\mathcal{X}\in\mathcal{S}$ $\;\Rightarrow\;$ limit $\epsilon\to 0$ exists (at best) as a *weak limit*:**

$$\langle H^*[N]\mathcal{X}|\Psi\rangle = \lim_{\epsilon\to 0}\,\langle \mathcal{X}|\hat{H}[N,\epsilon]\Psi\rangle \;\;, \qquad \mathcal{X}\in\mathcal{S}$$

- ***Ultralocal* action of unregulated Hamiltonian adds 'spiderwebs' (of size $\epsilon\to 0$) to spin network Γ, but cumbersome to evaluate (on $\mathcal{S}$) even for the simplest examples.**

Open issues and recent developments

- **Spin network wave functions difficult to interpret $\rightarrow$ semi-classical limit? Where is the 2-loop divergence?**
- **Quantum space-time covariance: since states $\mathcal{X}$ are diffeomorphism invariant by construction, do we only need to verify**

$$[\mathcal{H}[N], \mathcal{H}[N']]\mathcal{X} = 0 \;\Rightarrow \quad \textbf{no anomalies??}$$

  BUT: very different treatment of constraints makes space-time covariance of effective low energy theory doubtful.

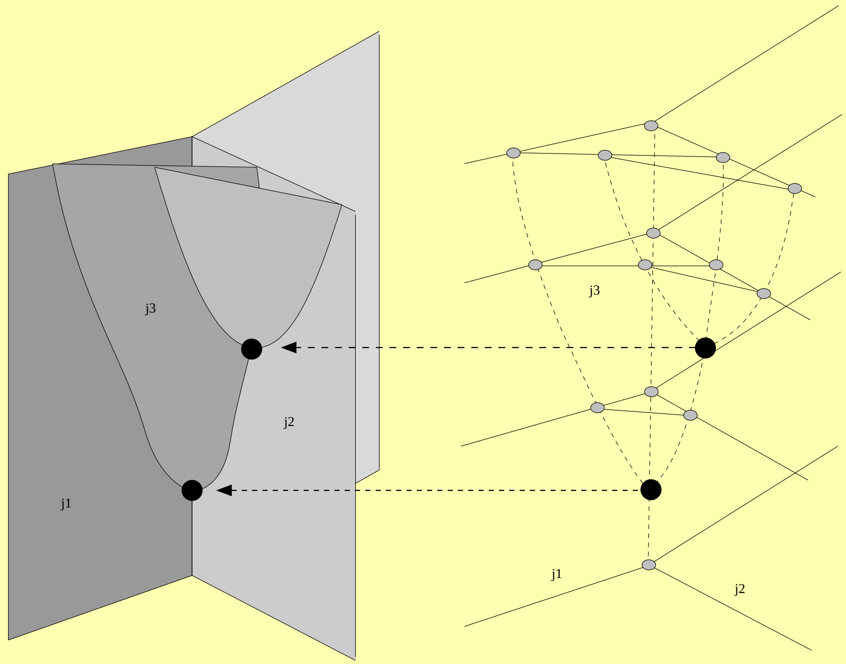
- **Numerous ambiguities (operator ordering, *etc.*)**
- **No anomalies/restrictions on matter couplings: anything goes?**

Recent work has shifted attention to

- **Loop Quantum Cosmology $\equiv$ mini-superspace LQG $\rightarrow$ 'resolve' Big Bang singularity?** [Bojowald(2001)]
- **'Covariant' approaches: Spin Foams, BF-theories,...**

Spin Foams (I)

→ **a 'covariant' version of canonical LQG?** [Reisenberger,Rovelli(1999)]



Spins now attached to $d=2$ *surfaces* rather than edges, and intertwiners attached to edges rather than vertices.

Link between LQG and SF exists only at level of kinematics ⇒ better to think of spin foams as novel models of lattice gravity.

Spin Foams (II)

Aim: emulate (in a rigorous way?) formal path integral

$$\langle \gamma \,|\, \gamma' \rangle = \int_{\gamma}^{\gamma'} \prod_{x \in \mathcal{M}} \mathcal{D} g_{\mu\nu}(x) \mathcal{D}(\text{matter}, \text{ghosts}) \exp\left(iS[g; ...]\right)$$

with spatial metrics $\gamma \in \mathrm{Riem}(\Sigma)/\mathrm{Diff}(\Sigma)$ **and** $\gamma' \in \mathrm{Riem}(\Sigma')/\mathrm{Diff}(\Sigma')$**.**

Space-time 'slab' $\mathcal{M}$ **bounded by 3-manifolds** Σ, Σ' $\rightarrow$ **analogously, Spin Foam** $\mathcal{F}(\Gamma, \Gamma')$ **is a 2-complex (consisting of faces, edges, and vertices) bounded above and below by spin networks** Γ **and** Γ'**.**

By definition, SF amplitudes must obey composition law

$$\mathcal{A}(\mathcal{F}_1 \circ \mathcal{F}_2) = \mathcal{A}(\mathcal{F}_1) \cdot \mathcal{A}(\mathcal{F}_2)$$

such that physical transition amplitudes are

$$\langle \Gamma \,|\, \Gamma' \rangle = \sum_{\text{all foams}\, \mathcal{F}(\Gamma, \Gamma')} \mathcal{A}(\mathcal{F}(\Gamma, \Gamma'))$$

But: 'sum over *all* spin foams' or refinement limit?

Cf. dynamical triangulations *vs.* quantum Regge calculus.

Spin Foams (III)

To arrive at candidate mathematical expressions for $\mathcal{A}$ start from 'BF-theory' and action $= \int B^{IJ} \wedge F^{IJ}(\omega)$ with spin connection $\omega^{IJ} \in \mathfrak{so}(4)$ or $\in \mathfrak{so}(1,3)$ (with obvious generalization to $D \neq 4$).

In order to relate this topological theory to GR (with propagating gravitons) need simplicity constraint $B^{IJ} + \gamma^{-1} * B^{IJ} = *(e^I \wedge e^J)$.

Quantization and transition to spin foams proceeds in three steps:

1. **Discretize classical BF theory on a simplicial complex**
2. **Quantize topological BF part of discretized theory (or 3.)**
3. **Impose simplicity constraint at quantum level (or 2.)**

Simplicial complex of 1. is *dual* to 2-complex defining spin foam:

4-simplex $\longleftrightarrow$ spin foam vertex v
3-simplex $\longleftrightarrow$ spin foam edge e
2-simplex $\longleftrightarrow$ spin foam face f

Quantization leads to expected association (spins to faces, intertwiners to edges), *except* that $SU(2)$ is replaced by $SO(4)$ (Euclidean spin foams) or $SO(1,3)$ (Lorentzian spin foams).

There are various possibilities to relate $SO(4)$ labels (j^+, j^-) or $SO(1,3)$ labels (ρ, n) to $SU(2)$ labels of LQG spin network:

- **EPRL model:** $|1+\gamma|\, j^+ = |1-\gamma|\, j^-$
- **Barrett-Crane model:** $j^+ = j^-$ **(≡ EPRL for $\gamma = \infty$)**
- **Lorentzian spin foam:** $\rho = \gamma n$

Dynamics defined via generalized *spin state sum* model

$$Z_{\mathcal{F}} = \sum_{\text{spins}} \prod_{f,e,v} A_f(\{j\}) \;\; A_e(\{j\}) \;\; A_v(\{j\})$$

with amplitudes for faces f, edges e and vertices v of 2-complex.

For instance, $A_v = \{10j\}$ or $\{15j\}$ symbol, $A_f \propto (2j_f + 1) \propto$ 'area',... but many choices (*e.g. valences of vertices,...*)

Open issues and questions

- **Is imposition of simplicity constraint *after* quantization of topological BF theory consistent?**
- **Sum over spin foams or refinement limit?**

  NB: this is not an issue for topological $D = 3$ theory !
- **Spin Foam = *actual* or *regularized* quantum space-time?**
- **Emergence of a length scale and of space-time continuum?**
- **Emergence of classical gravity at long distances for a given truncation (related to asymptotics of invariant tensors)?**
- **Convergence of sums over spins $\{j\}$ for given spin foam $\mathcal{F}$?**

  $\rightarrow$ this is an IR issue, rather than a UV issue (controversial!)

Numerous ambiguities: valences of spin foam vertices, choice of amplitude factors, simplicity constraints, *etc.* (not to mention inclusion of matter couplings!)

Hope: fewer universality classes $\Rightarrow$ fewer ambiguities?

Group Field Theory

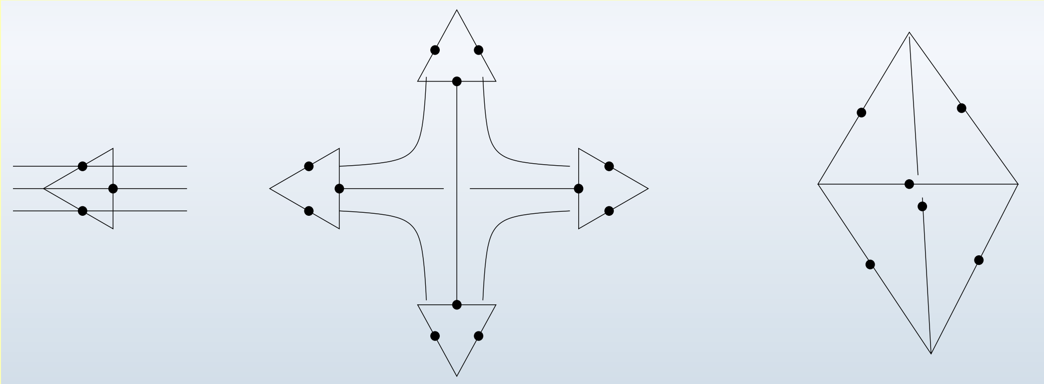
[Boulatov(1992); Ooguri(1995); DePietri,Freidel,Krasnov,Perez,Reisenberger,Rovelli(1999)]

Aim: **reproduce *spin foam amplitudes via Feynman graphs* of an abstractly defined (space-time-less!) field theory defined on a group manifold with (real or complex) fields** $\varphi(g_{1234})$ **and** $g_{1234} \equiv (g_1, g_2, g_3, g_4) \in G \otimes G \otimes G \otimes G$ **for** $D = 4$ **space-time dimensions, and**

$$S = \int dg_{1234} dg'_{1234}\, \varphi(g_{1234})\, K(g^{-1}_{1234}\, g'_{1234})\, \varphi(g'_{1234}) + \lambda S_{int}$$

where interaction is specified by combinatorics of spin foam:

$$S_{int} = \int \prod_n dg^{(n)}_{1234}\, \mathcal{V}(\{g^{(n)}_{1234}\}) \prod_n \varphi(g^{(n)}_{1234})$$



GFT correlators are defined via path integral

$$\langle \cdots \rangle \propto \int \prod_{g_{1234} \in G \otimes G \otimes G \otimes G} \mathcal{D}\varphi(g_{1234}) \exp\left(iS[\varphi(g)]\right)(\cdots)$$

Advantage: expansion in λ produces combinatorics of diagrams *etc.* as for ordinary Feynman path integrals $\Rightarrow$ this prescription *automatically defines* the 'sum over all spin foams' !

Idea: φ creates/annihilates quanta of (triangulated) space-time $\Rightarrow$ GFT $\equiv$ second quantization of LQG?

- **GFTs are related to tensor theories (generalizing relation *strings* $\leftrightarrow$ *matrix models* $\leftrightarrow$ *planar QFT*)**
- **Fourier transform $\Rightarrow$ non-commutative field theory.**
- **Several *renormalizable* GFT models are known.**
- **Matter couplings known explicitly only for $D = 3$, but not known (and awkward?) for $D \geq 4$.**

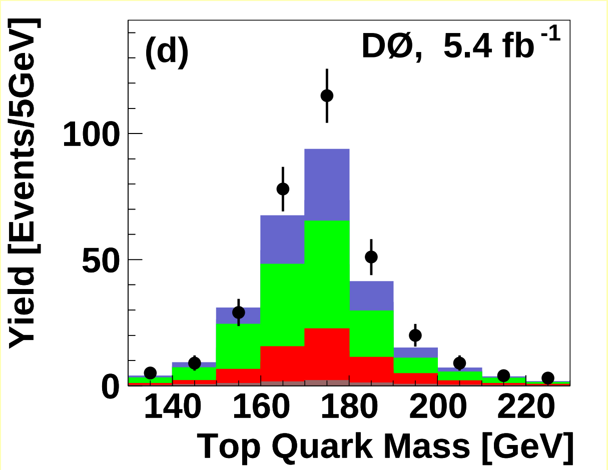
Some general questions

- How much background independence do we need?
- Is it possible to quantize in terms of gauge invariant variables only (does not seem to work in QFT)?

Background Independence

According to Wikipedia, *Background Independence*, also called Universality, is the concept or assumption, fundamental to all physical sciences, that the nature of reality is consistent throughout space and time. More specifically, no observer can, under any circumstances, perform a measurement that yields a result logically inconsistent with a previous measurement, under a set of rules that are independent of where and when the observations are made. More concretely: a proper formulation of quantum gravity should not depend on a given (space-time) metric or any other given background structure!

Of course, everyone agrees on this *desideratum*, but ....



Some general questions

- How much background independence do we need?
- Is it possible to quantize in terms of gauge invariant variables only (does not seem to work in QFT)?
- Regularization vs. renormalization?
- No indication whatsoever that matter may be needed for consistent quantization of gravity.
- Continuum limit and semi-classical ($\hbar \to 0$) limit?
- Emergence of a physical length scale and fate of short distance singularities?
- Which is the 'right' SF or GFT: are there symmetry principles or other guidelines for finding it?

(My) Summary

- **Many innovative proposals for a non-perturbative description of quantum space-time and geometry.**
- **Similarities, but no convergence of *ansätze* and ideas.**
- ***Complete* background independence invariably entails difficulties in recovering classical limit, and in particular understanding fate of 2-loop divergence.**
- **Numerous ambiguities:**
  - 10^{500} **'consistent' Hamiltonians?**
  - 10^{500} **'consistent' Spin Foams?**
  - 10^{500} **'consistent' RG flows/universality classes?**

  $\Rightarrow$ **non-predictivity** $\equiv$ **non-renormalizability in a different guise?**
- **Confirmation or refutation by experiment/observation even more of a challenge than for string theory!**