Quantum Gravity, from the atoms of space to cosmology

The Universe as a Quantum Condensate

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24/07/2015

Quantum spacetime: the difficult path from microstructure to macrophysics

Quantum Gravity problem:
identify microscopic d.o.f. of quantum spacetime and their fundamental dynamics

derive effective (QG-inspired) models for macroscopic continuum physics:
explain features of early Universe, obtain testable QG predictions

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identify microscopic d.o.f. of quantum spacetime and their fundamental dynamics

various approaches: group field theory, loop quantum gravity

derive effective (QG-inspired) models for (quantum) cosmology:
explain features of early Universe, obtain testable QG predictions

various models: loop quantum cosmology, ...

task is daunting (compare with analogue problem in condensed matter theory)

Group Field Theory: convergence of approaches

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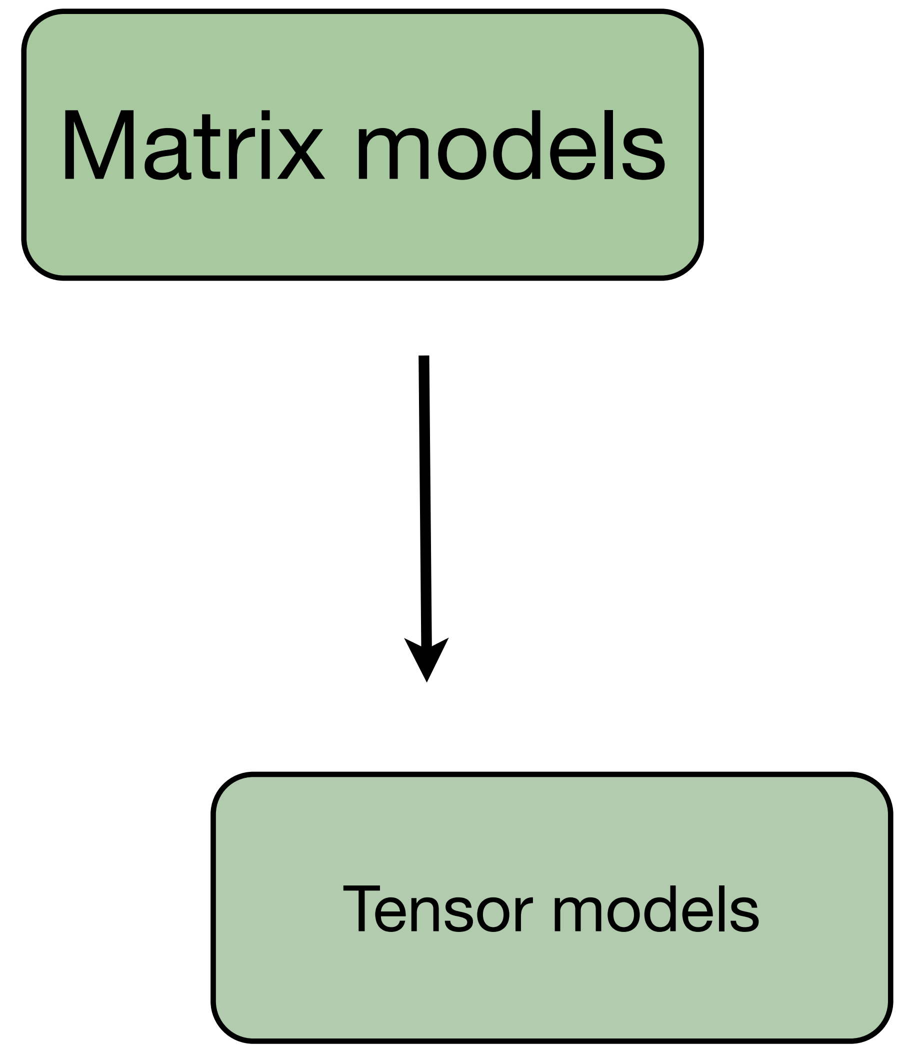
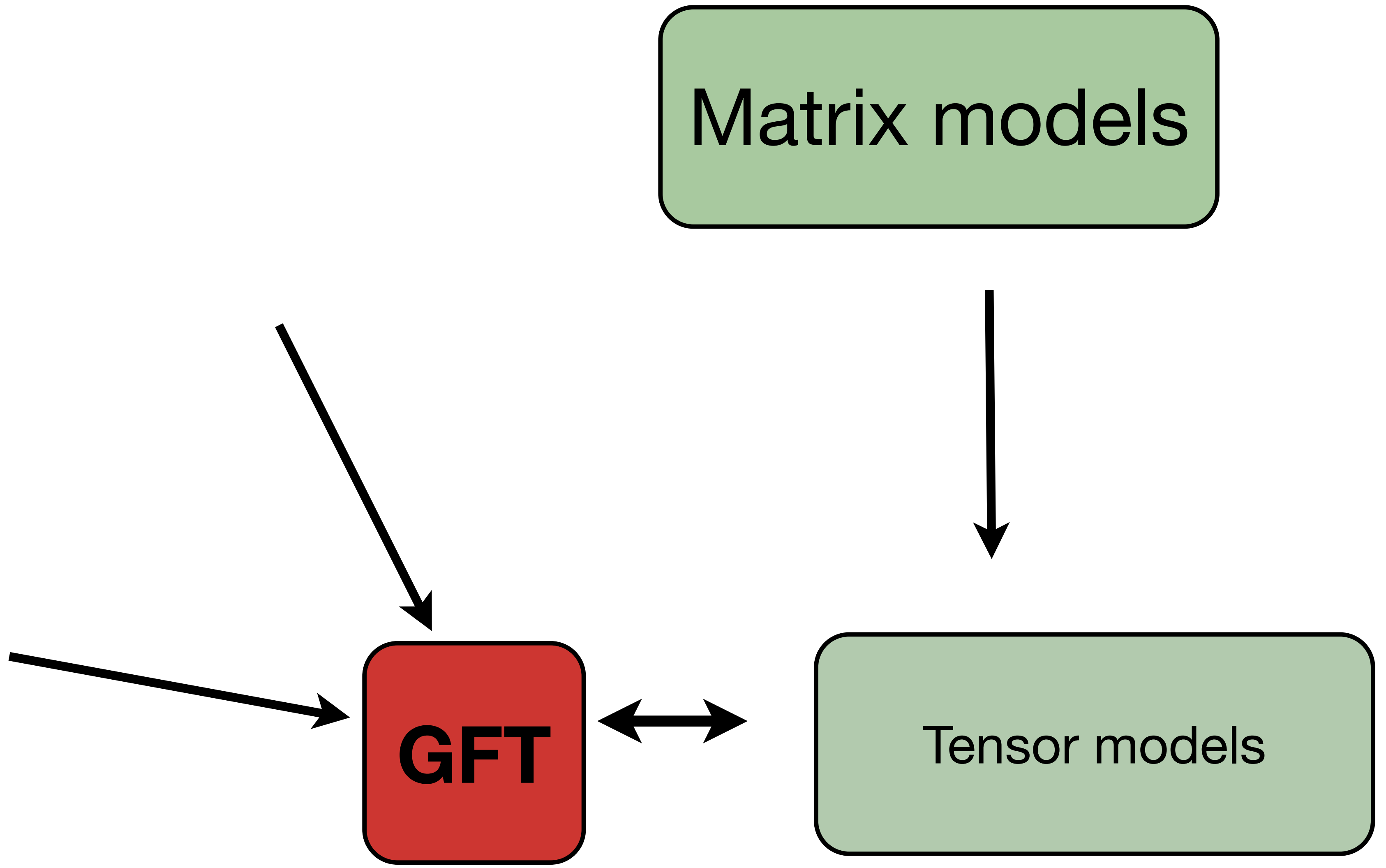
Matrix models

Group Field Theory: convergence of approaches



Group Field Theory: convergence of approaches



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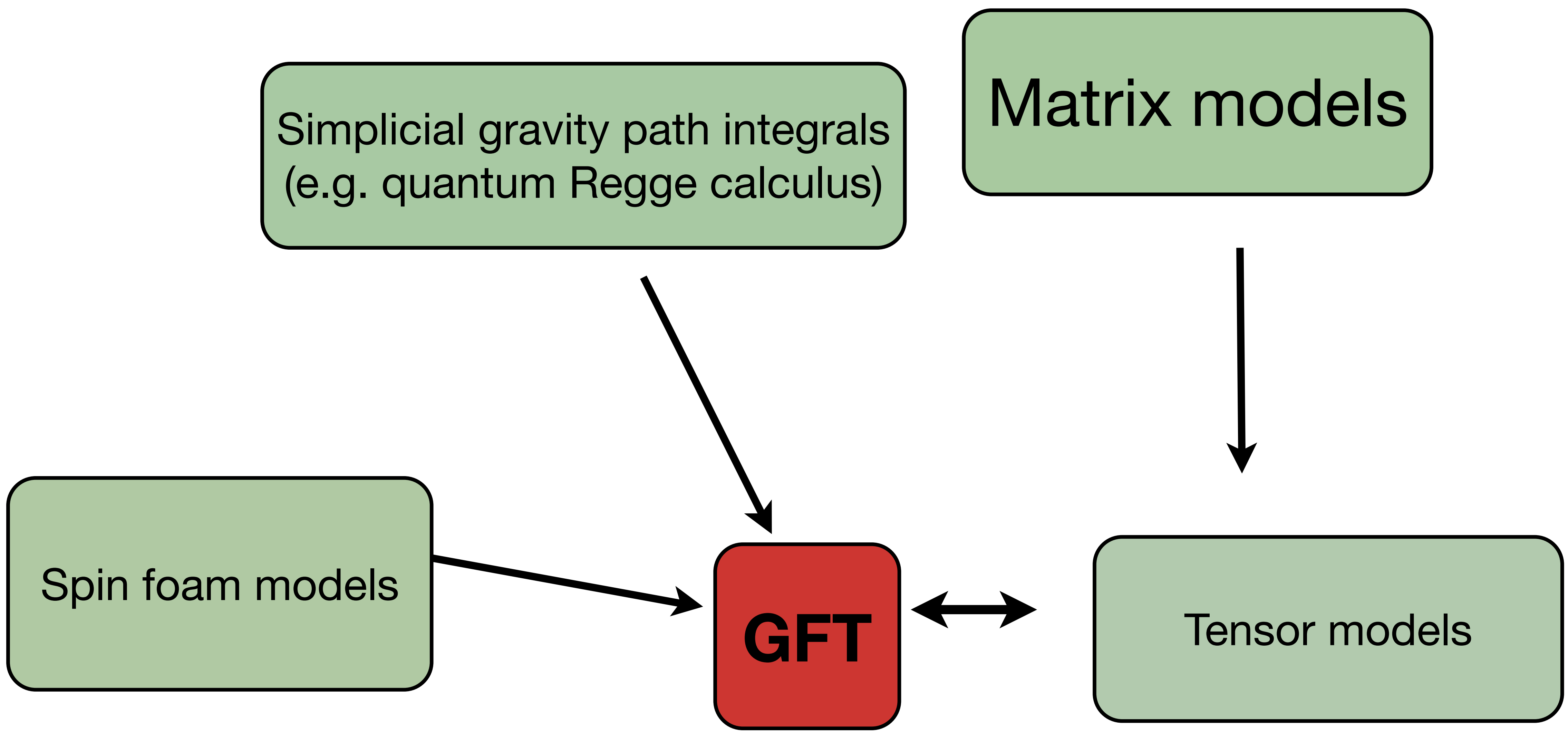

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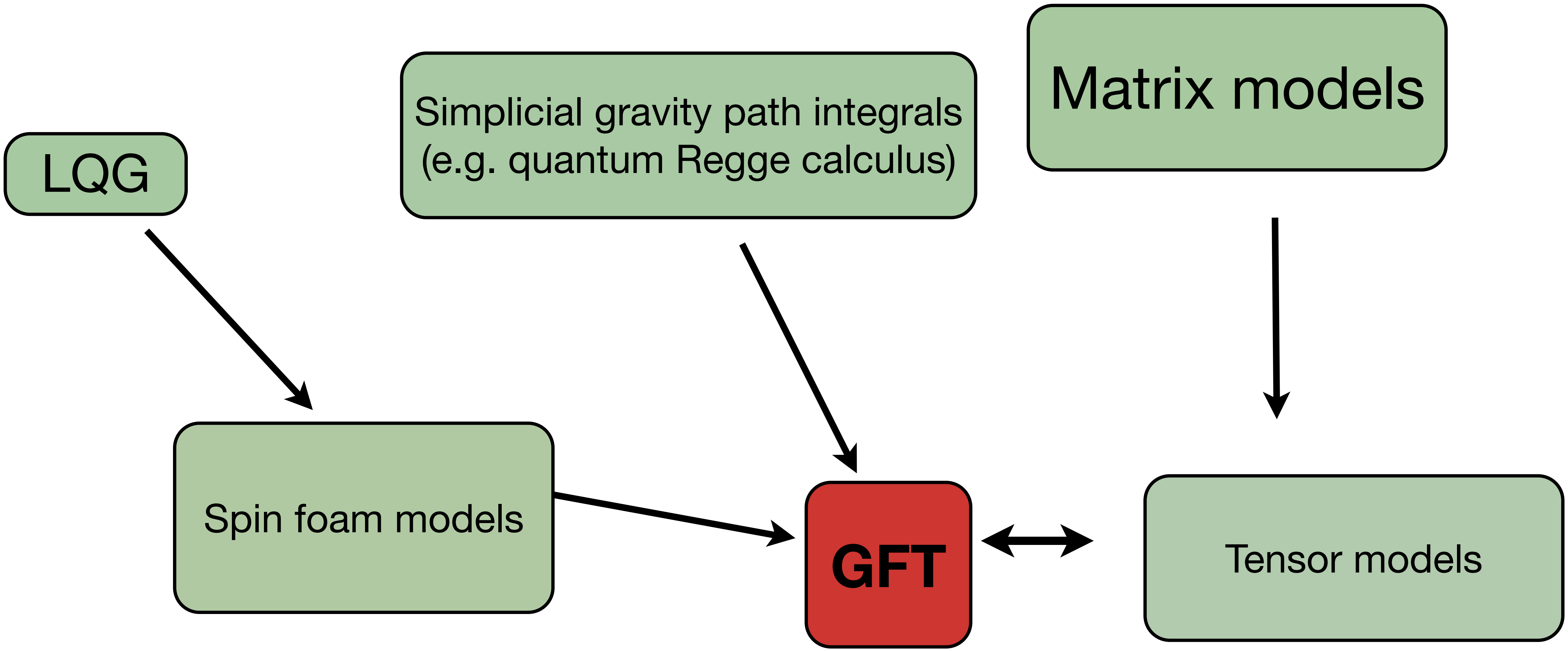

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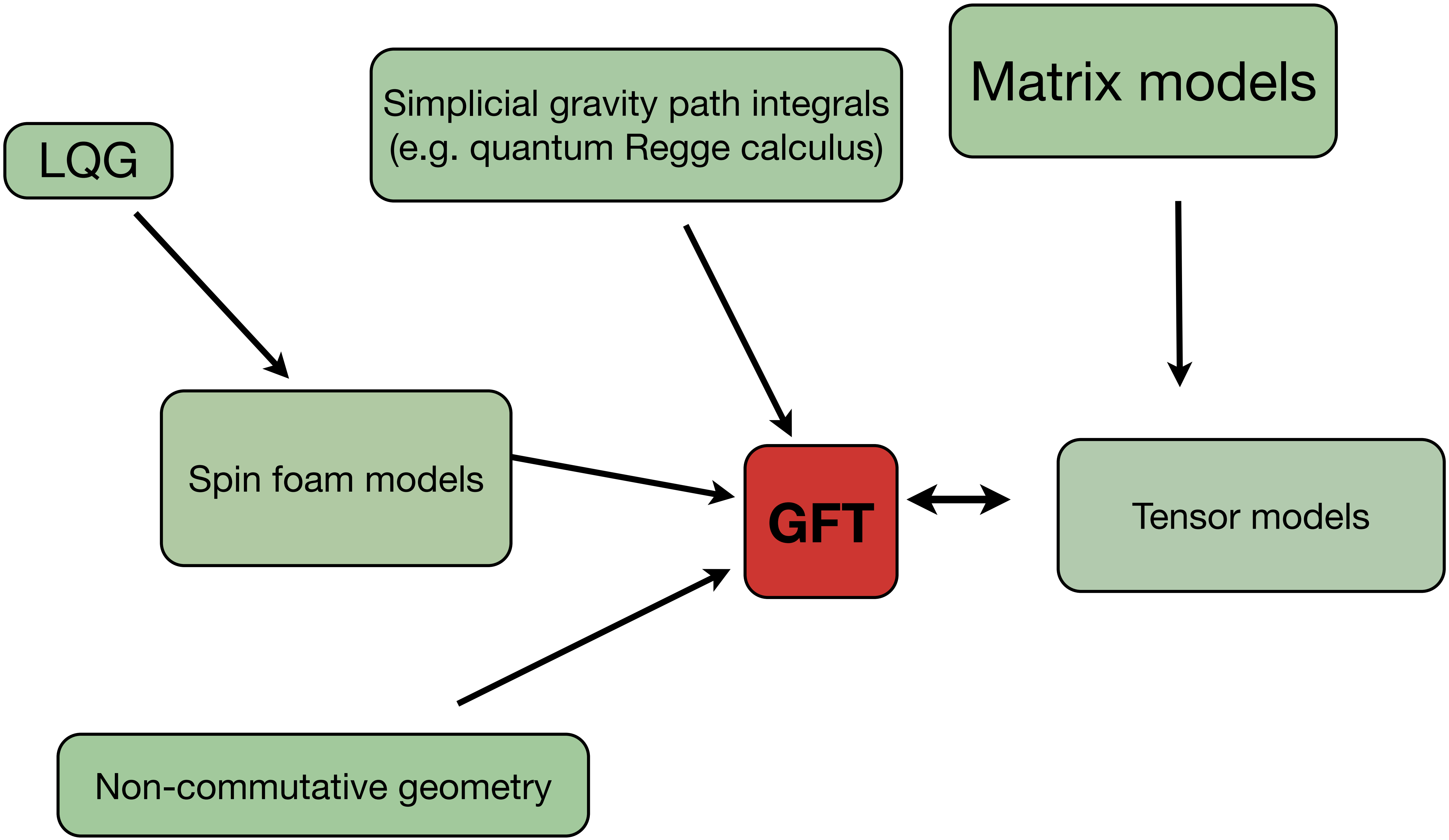

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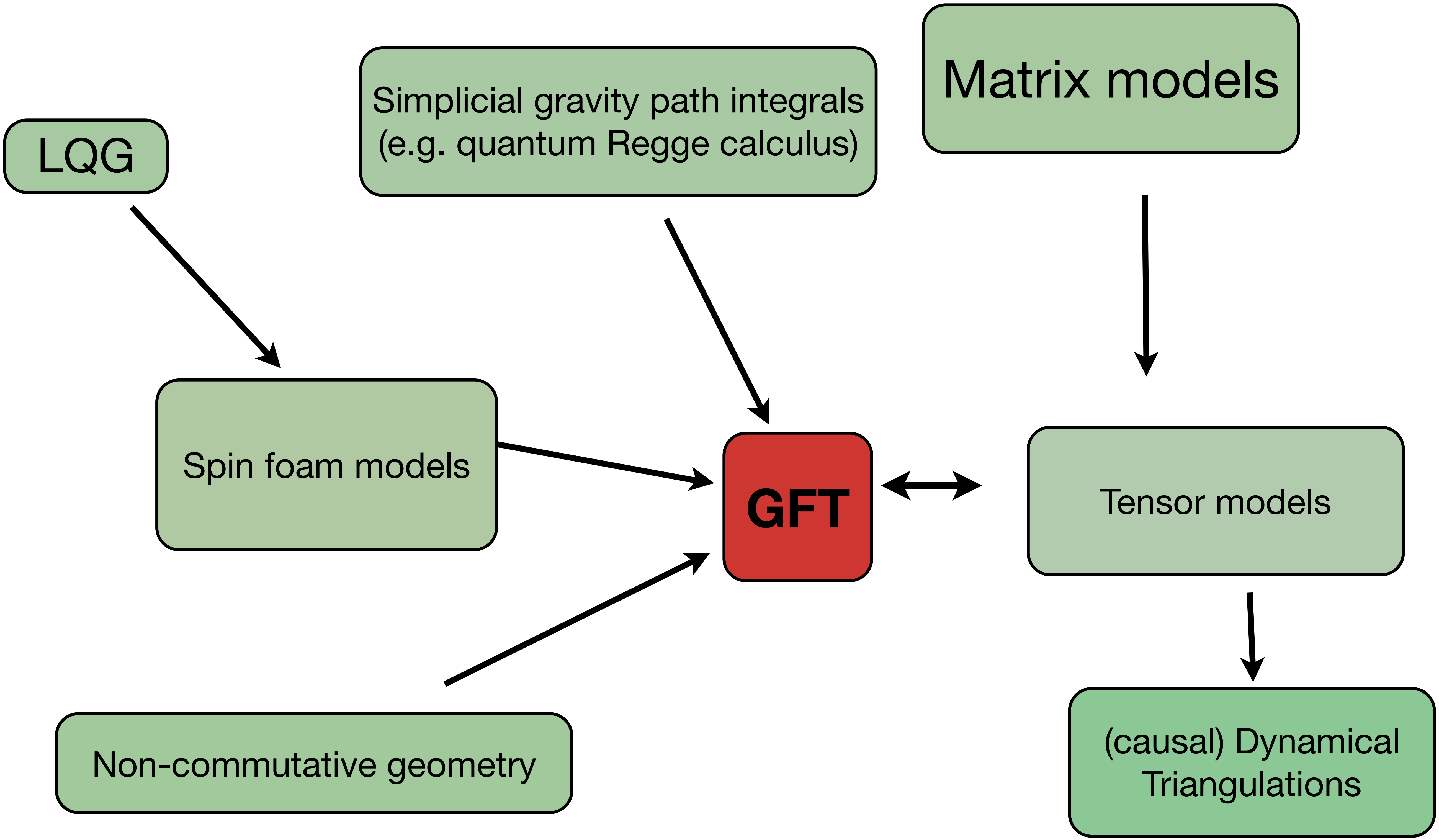

Group field theories

Quantum field theories over group manifold G (or corresponding Lie algebra) $\varphi : G^{\times d} \rightarrow \mathbb{C}$

relevant classical phase space for “GFT quanta”: $(\mathcal{T}^* G)^{\times d} \simeq (\mathfrak{g} \times G)^{\times d}$

can reduce to subspaces in specific models depending on conditions on the field

d is dimension of “spacetime-to-be”

example: d=4 $\varphi(g_1, g_2, g_3, g_4) \leftrightarrow \varphi(B_1, B_2, B_3, B_4) \rightarrow \mathbb{C}$

can be defined for any (Lie) group and dimension d, any signature, ...

very general framework; interest rests on specific models/use

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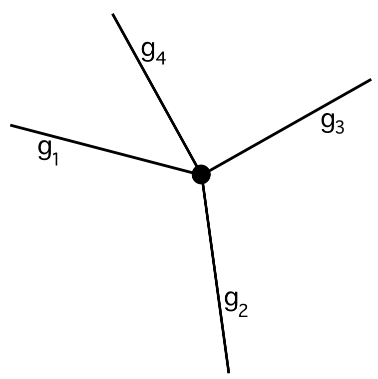

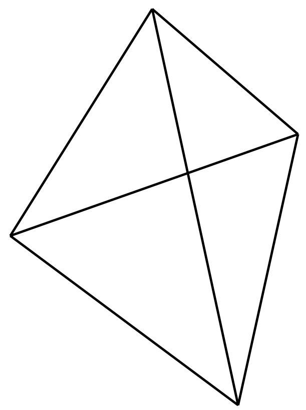

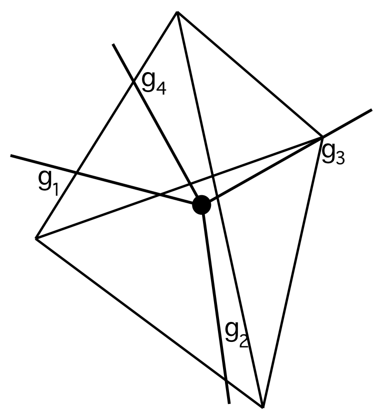

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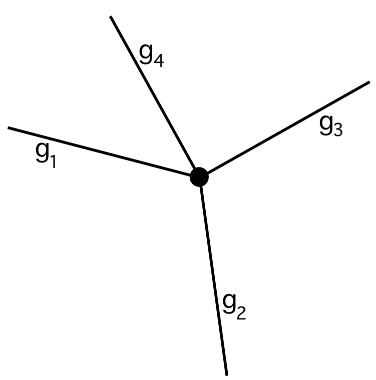

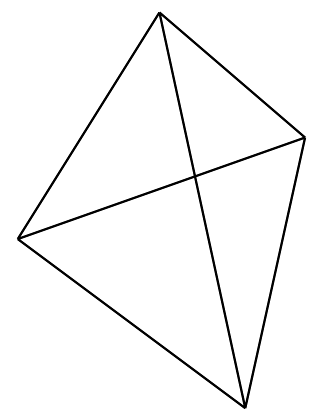

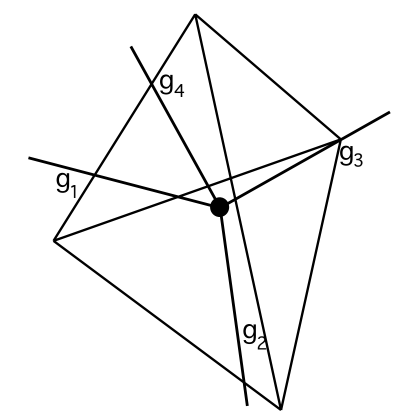

generic quantum state: arbitrary collection of spin network vertices (including glued ones) or tetrahedra (including glued ones)

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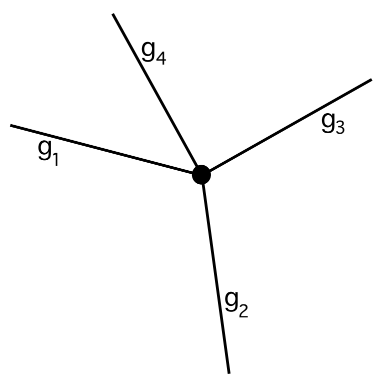

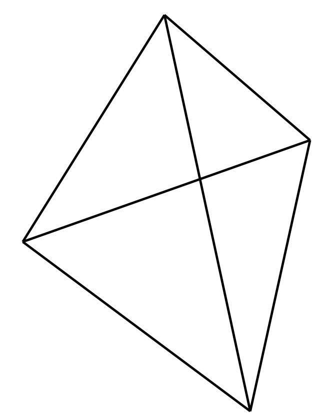

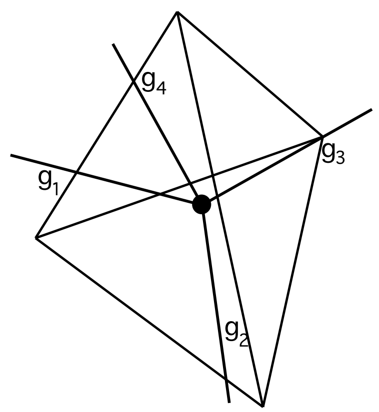

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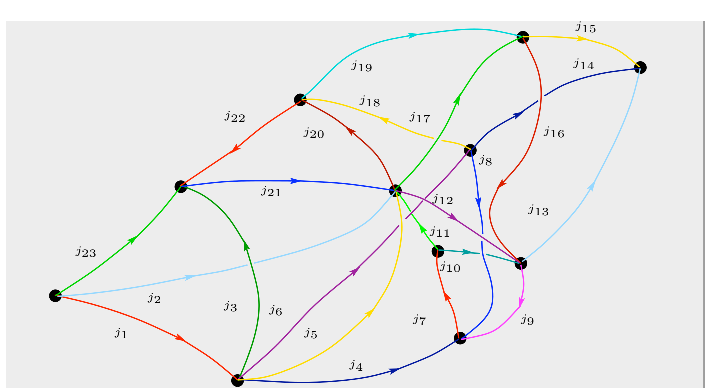

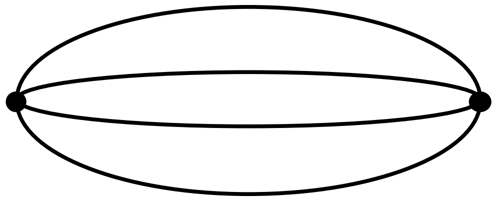

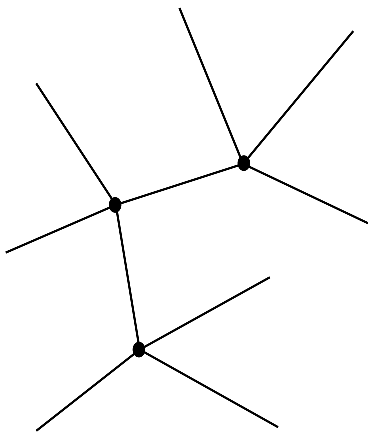

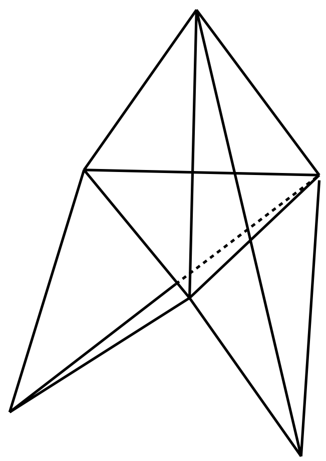

Group field theories

classical action: kinetic (quadratic) term + (higher order) interaction (convolution of GFT fields)

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

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in pairing of field arguments

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combinatorics of field arguments in interaction: gluing of 5 tetrahedra across common triangles, to form 4-simplex ("building block of spacetime")

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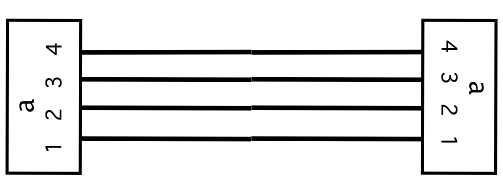

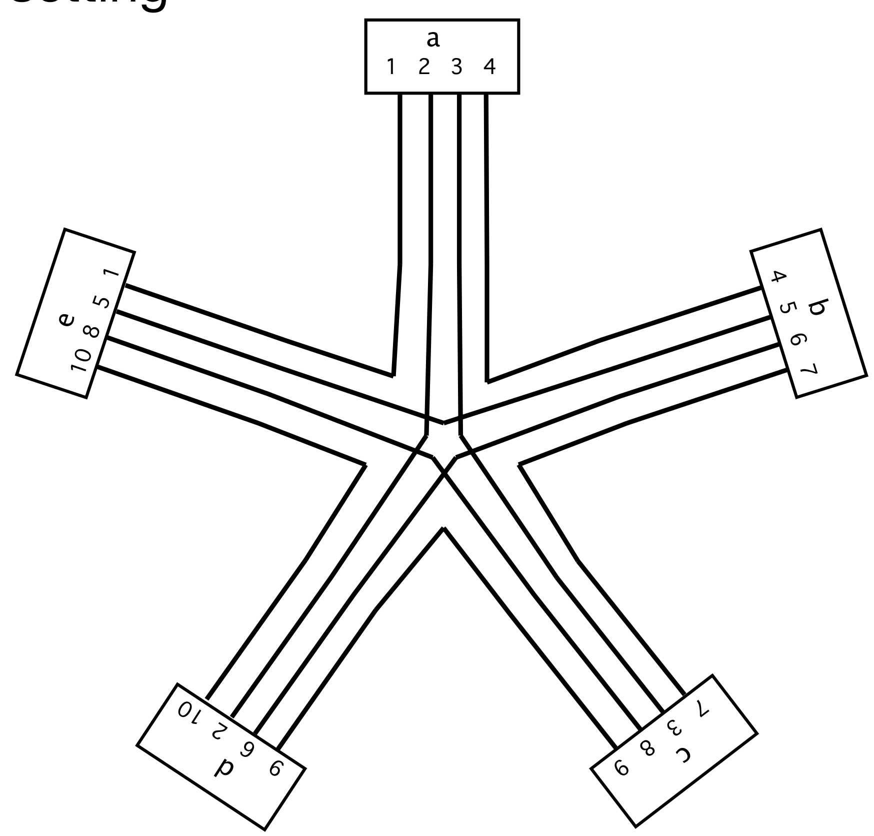

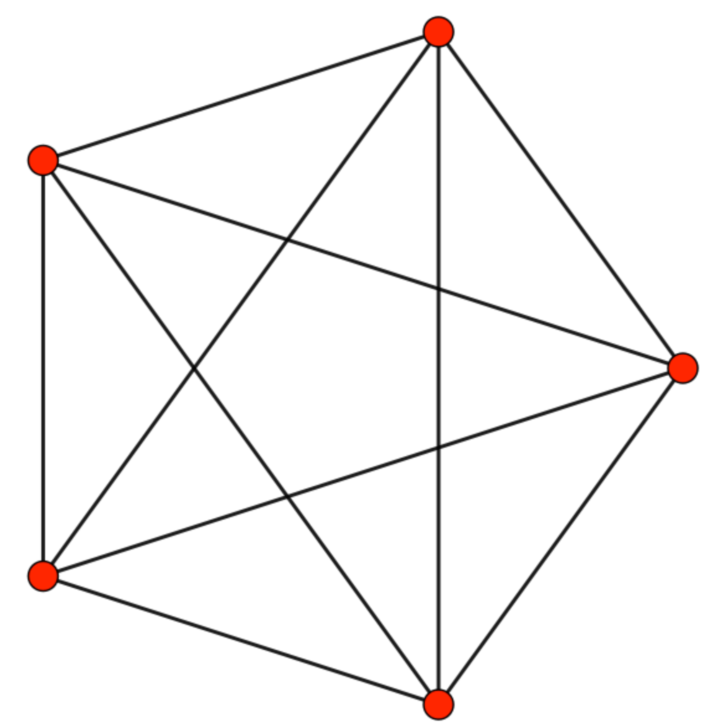

Group field theories

Feynman perturbative expansion around trivial vacuum

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

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Feynman diagrams (obtained by convoluting propagators with interaction kernels) =

= stranded diagrams dual to cellular complexes of arbitrary topology

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

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equivalently:

- spin foam models (sum-over-histories of spin networks)

  Reisenberger,Rovelli, '00

- lattice path integrals (with group+Lie algebra variables)

  A. Baratin, DO, '11

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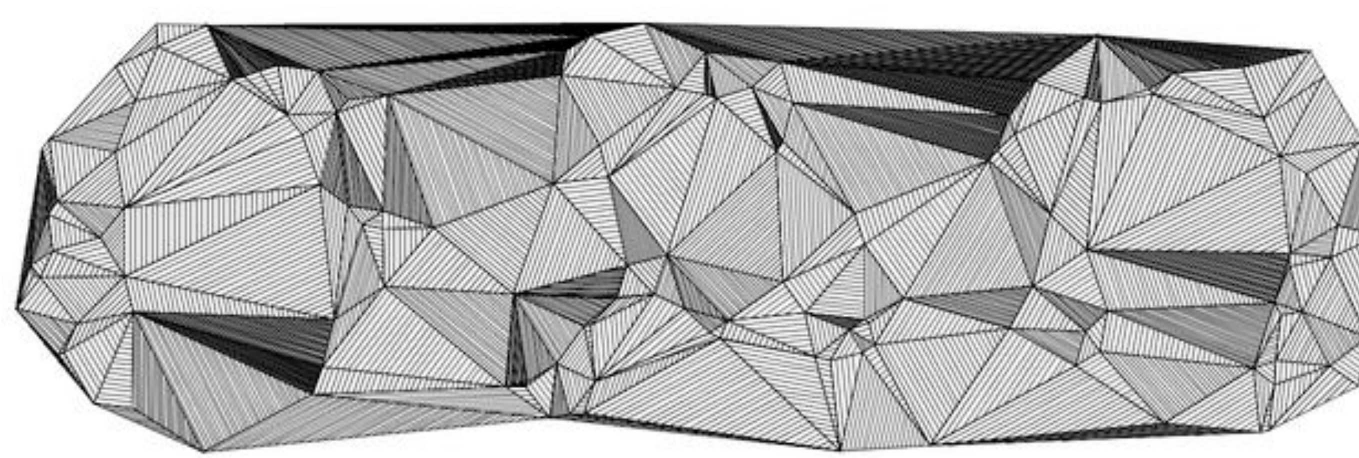

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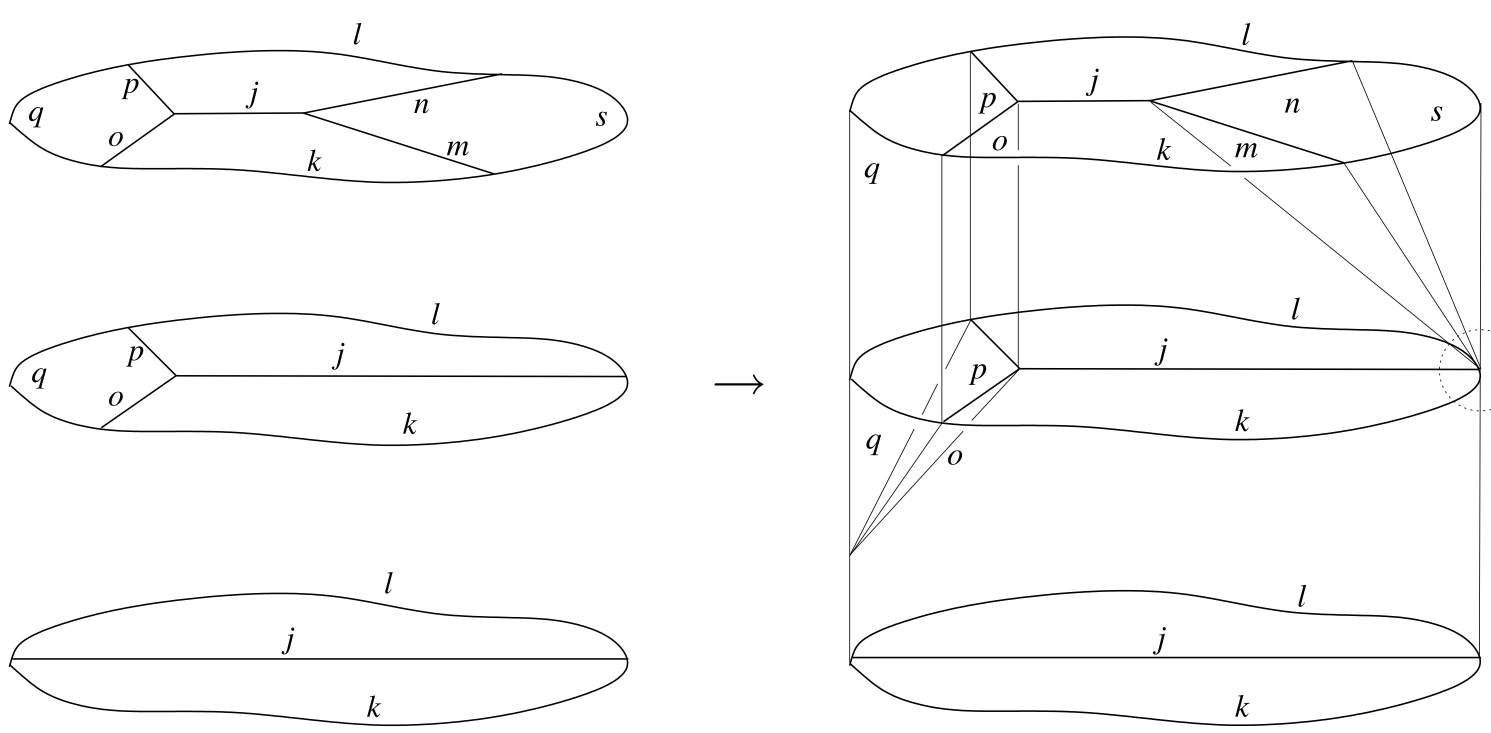

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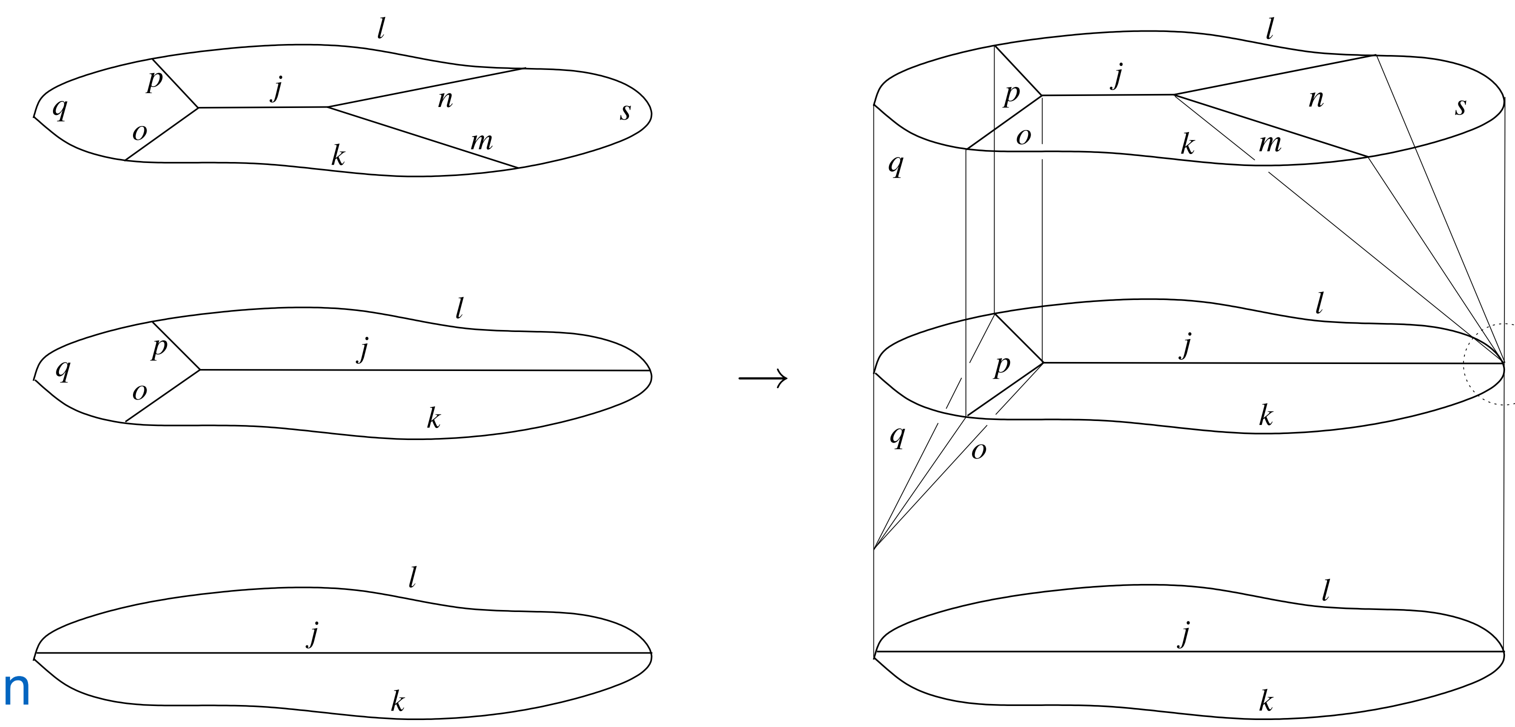
all current spin foam models have GFT formulation



GFTs, loop quantum gravity, spin foam models

appropriate conditions on GFT fields or GFT dynamics (and choice of data) turn GFT Feynman amplitudes into lattice gauge theories/discrete gravity path integrals/spin foam models

e.g. gauge invariance of GFT fields under diagonal action of group G

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$$\forall h \in \mathrm{SO}(3), \qquad \varphi_\ell(hg_1, hg_2, hg_3) \, = \, \varphi_\ell(g_1, g_2, g_3)$$

+ simplicial interaction

with only delta functions

can be computed in different (equivalent) representations (group, spin, Lie algebra)

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$$S_{kin}[\varphi_\ell] = \int [\mathrm{d}g_i]^3 \sum_{\ell=1}^{4} \varphi_\ell(g_1, g_2, g_3)\overline{\varphi_\ell}(g_1, g_2.g_3),$$

$$\begin{aligned} S_{int}[\varphi_\ell] \quad &= \quad \lambda \int [\mathrm{d}g_i]^6\, \varphi_1(g_1, g_2, g_3)\varphi_2(g_3, g_4, g_5)\varphi_3(g_5, g_2, g_6)\varphi_4(g_6, g_4, g_1) \\ &\quad +\lambda \int [\mathrm{d}g_i]^6\, \overline{\varphi_4}(g_1, g_4, g_6)\overline{\varphi_3}(g_6, g_2, g_5)\overline{\varphi_2}(g_5, g_4, g_3)\overline{\varphi_1}(g_3, g_2, g_1) \end{aligned}$$

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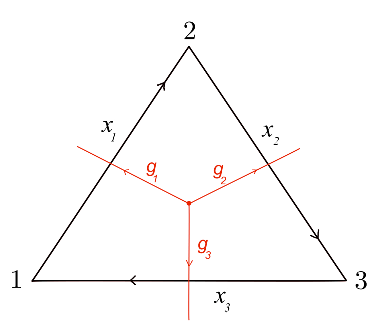
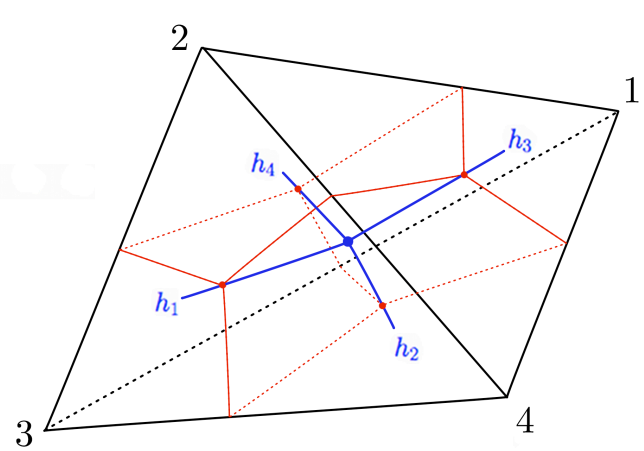
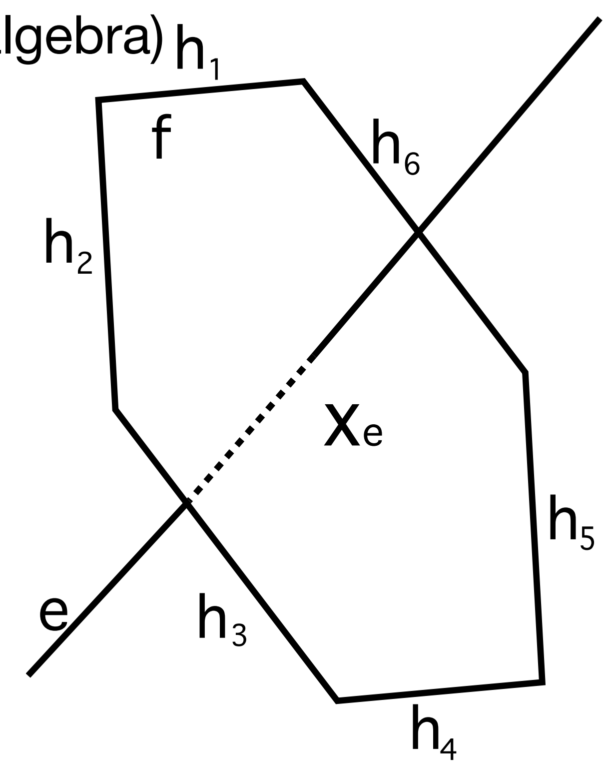


$$\varphi(g_1, g_2, g_3) \; \leftrightarrow \; \varphi(x_1, x_2, x_3)$$





discretization of: $\quad S(e,\omega) = \int Tr(e \wedge F(\omega))$

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$$\mathcal{A}_\Gamma \;=\; \int \prod_l \mathrm{d}h_l \prod_f \delta\left(H_f(h_l)\right) = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(\overrightarrow{\prod}_{l\in\partial f} h_l\right) =$$

$$= \sum_{\{j_e\}} \prod_e d_{j_e} \prod_\tau \left\{ \begin{array}{ccc} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{array} \right\} = \int \prod_l [\mathrm{d}h_l] \prod_e [\mathrm{d}^3 x_e] \, e^{i \sum_e \mathrm{Tr}\, x_e H_e}$$

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lattice gauge theory formulation of 3d gravity/BF theory

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$\forall h \in \mathrm{SO}(3), \qquad \varphi_\ell(hg_1, hg_2, hg_3) \,=\, \varphi_\ell(g_1, g_2, g_3)$ with only delta functions

can be computed in different (equivalent) representations (group, spin, Lie algebra)

$$\mathcal{A}_\Gamma \;=\; \int \prod_l \mathrm{d}h_l \prod_f \delta\left(H_f(h_l)\right) = \int \prod_l \mathrm{d}h_l \prod_f \delta\left(\overrightarrow{\prod}_{l\in\partial f} h_l\right) =$$

lattice gauge theory formulation of 3d gravity/BF theory

$$= \sum_{\{j_e\}} \prod_e d_{j_e} \prod_\tau \left\{ \begin{array}{ccc} j_1^\tau & j_2^\tau & j_3^\tau \\ j_4^\tau & j_5^\tau & j_6^\tau \end{array} \right\} = \int \prod_l [\mathrm{d}h_l] \prod_e [\mathrm{d}^3 x_e]\, e^{i\sum_e \mathrm{Tr}\, x_e H_e}$$

spin foam formulation of 3d gravity/BF theory

GFTs, loop quantum gravity, spin foam models

appropriate conditions on GFT fields or GFT dynamics (and choice of data) turn GFT Feynman amplitudes into lattice gauge theories/discrete gravity path integrals/spin foam models

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lattice gauge theory formulation of 3d gravity/BF theory

spin foam formulation of 3d gravity/BF theory

discrete 1st order path integral for 3d gravity/BF theory on simplicial complex dual to GFT Feynman diagram

GFTs, loop quantum gravity, spin foam models

GFT models of 4d gravity:

based on classical (Plebanski) formulation of GR as BF theory + (simplicity) constraints

start from GFT formulation of 4d BF theory
+ impose simplicity constraints (geometricity of simplicial structures)

(Barbieri, Baez, Barrett, Crane, Reisenberger, Perez, De Pietri, Engle, Pereira, Freidel, Krasnov, Rovelli, Livine, Speziale, Baratin, DO, ...)

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decompose GFT field in SU(2) data + geometricity conditions

↓

GFT dynamics to LQG quantum states

GFTs, loop quantum gravity, spin foam models

second quantized version of Loop Quantum Gravity
but dynamics not derived from canonical quantization of GR

DO, 1310.7786 [gr-qc]
DO, J. Ryan, J. Thuerigen, ‘14

(LQG spin network states ~ many-particles states, “particle” ~ spin network vertex)

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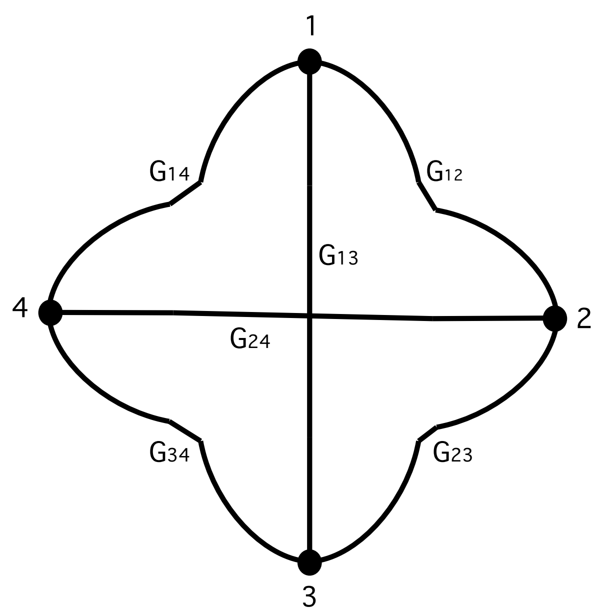

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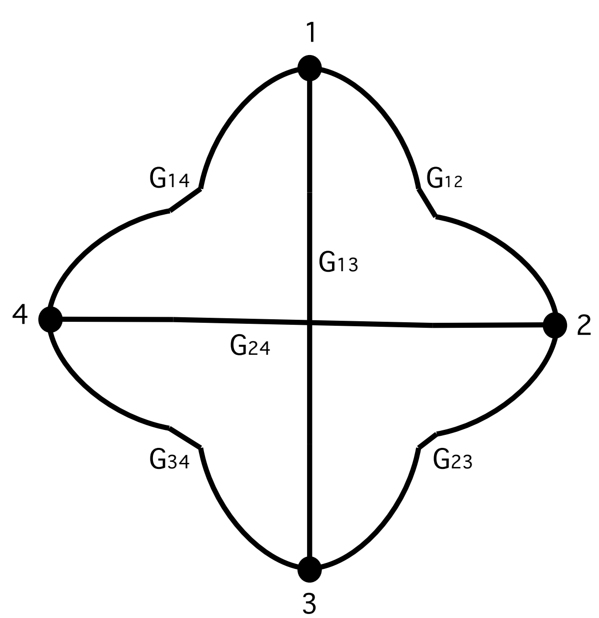

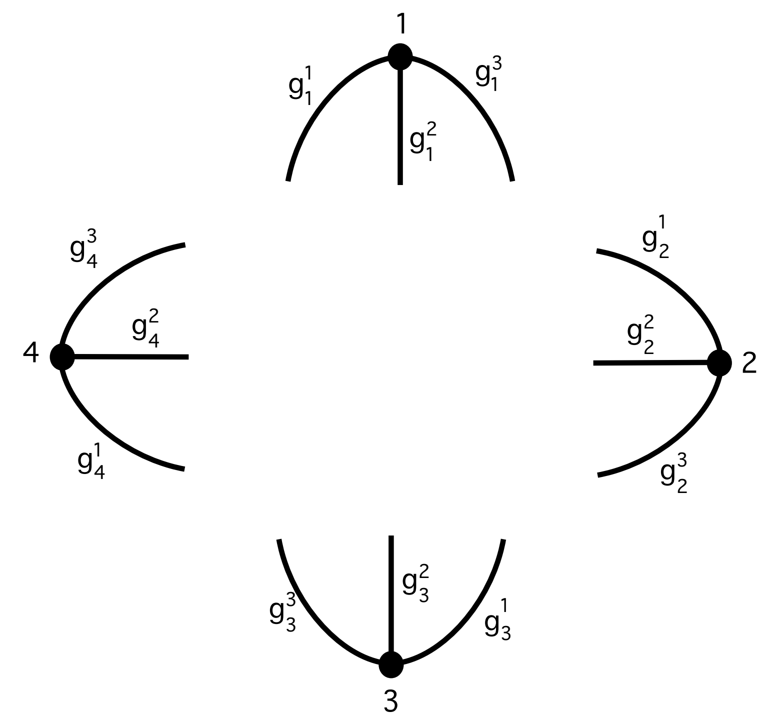

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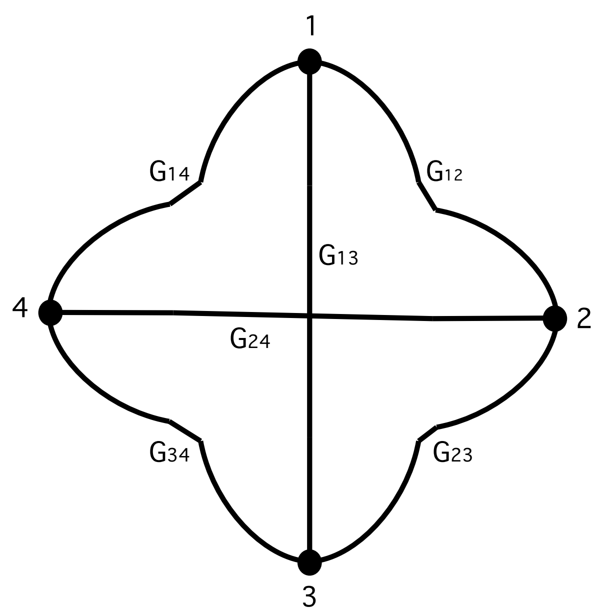

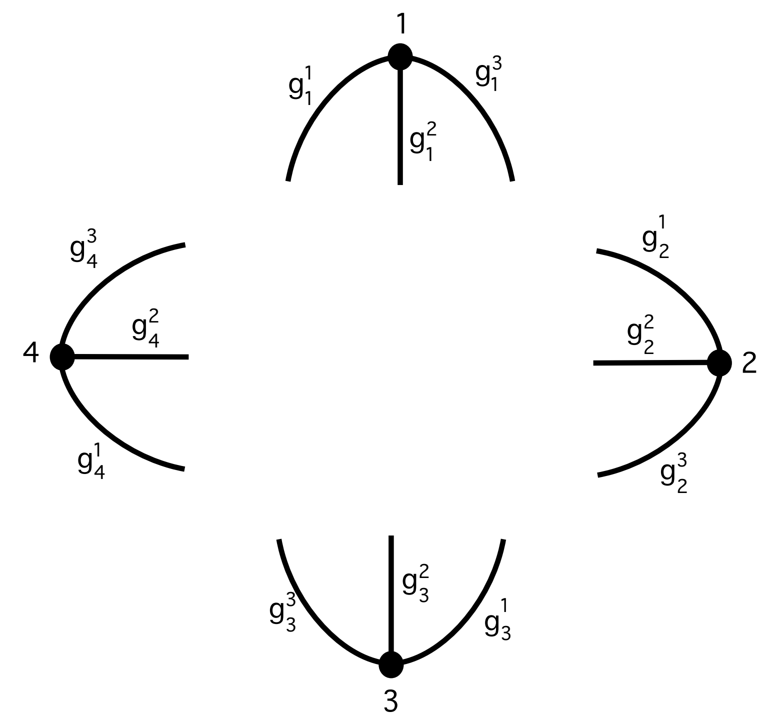

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any LQG observable has a 2nd quantised, GFT counterpart

choice of LQG dynamics (Hamiltonian constraint operator) translates into choice of GFT action

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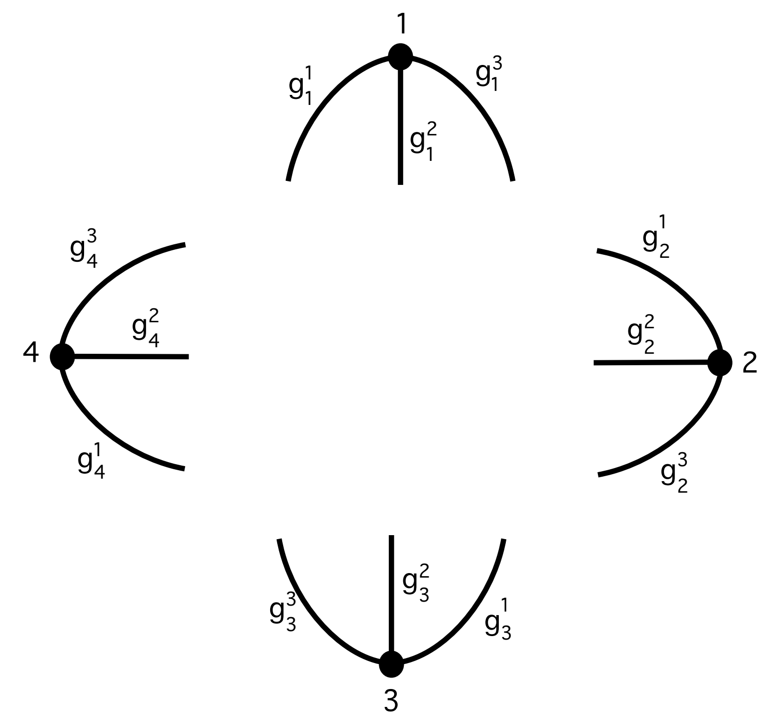

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QFT methods (i.e. GFT reformulation of LQG and spin foam models) useful to address physics of large numbers of LQG d.o.f.s, i.e. many and refined graphs (continuum limit)

(superpositions of "many-vertices" states, refinement as creation of new vertices, etc)

1. making sense of quantum dynamics and LQG partition function (correlations)
2. understanding LQG phase structure
3. extracting effective continuum dynamics

1st message

we have a solid candidate formalism for a theory of quantum gravity (a QFT for the "atoms of quantum space")

grounded in LQG (and discrete gravity, tensor models)

rigorous mathematics, clear pre-geometric meaning

promising fundamental dynamical models

lots of results ……..

Quantum spacetime:
the difficult path from microstructure to cosmology

Quantum Gravity problem:
identify microscopic d.o.f. of quantum spacetime and their fundamental dynamics

derive effective (QG-inspired) models for fundamental (quantum) cosmology:
explain features of early Universe, obtain testable QG predictions

various models: loop quantum cosmology, ...

task is daunting (imagine analogue problem in condensed matter theory)

The problem of the continuum limit in QG

new (non-geometric, non-spatio-temporal) physical degrees of freedom (“building blocks”) for space-time

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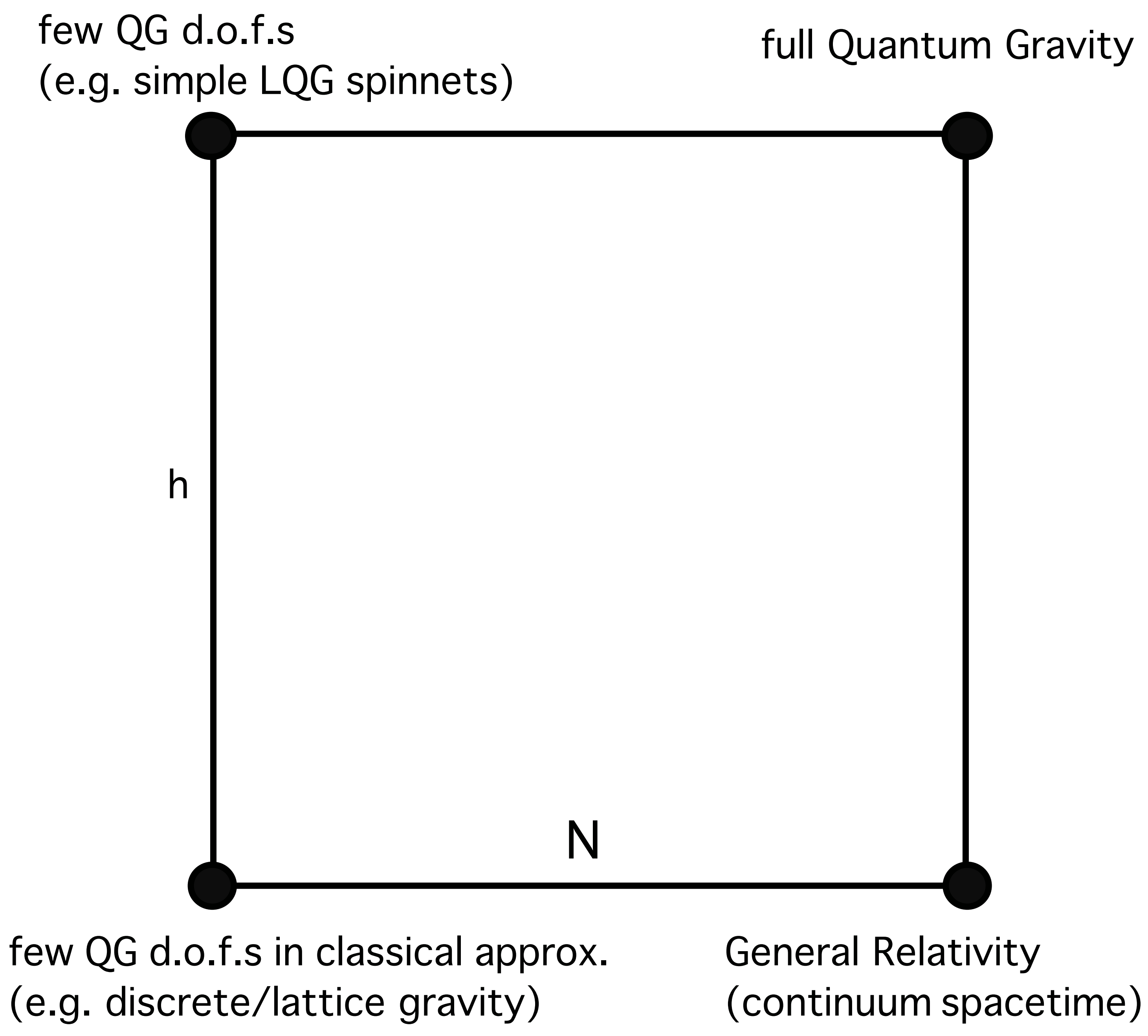
GFTs are a formulation of LQG/spin foams that is most suited to tackle this problem, thanks to QFT tools

Moving along the N-direction: the case of QG

continuum approximation very different (conceptually and technically) from classical approximation



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(collective behaviour of many interacting degrees of freedom):
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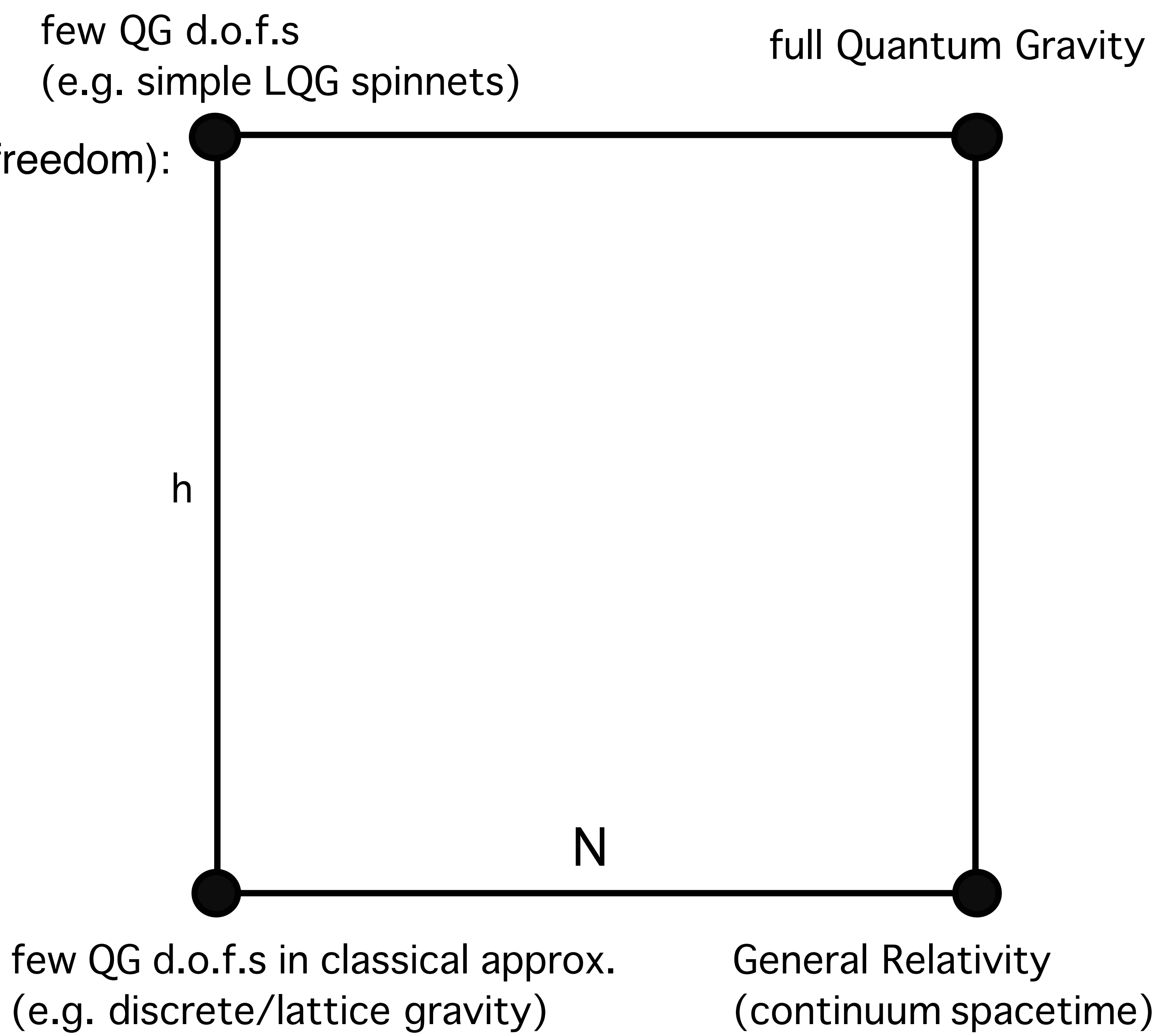
h-direction: classical approximation



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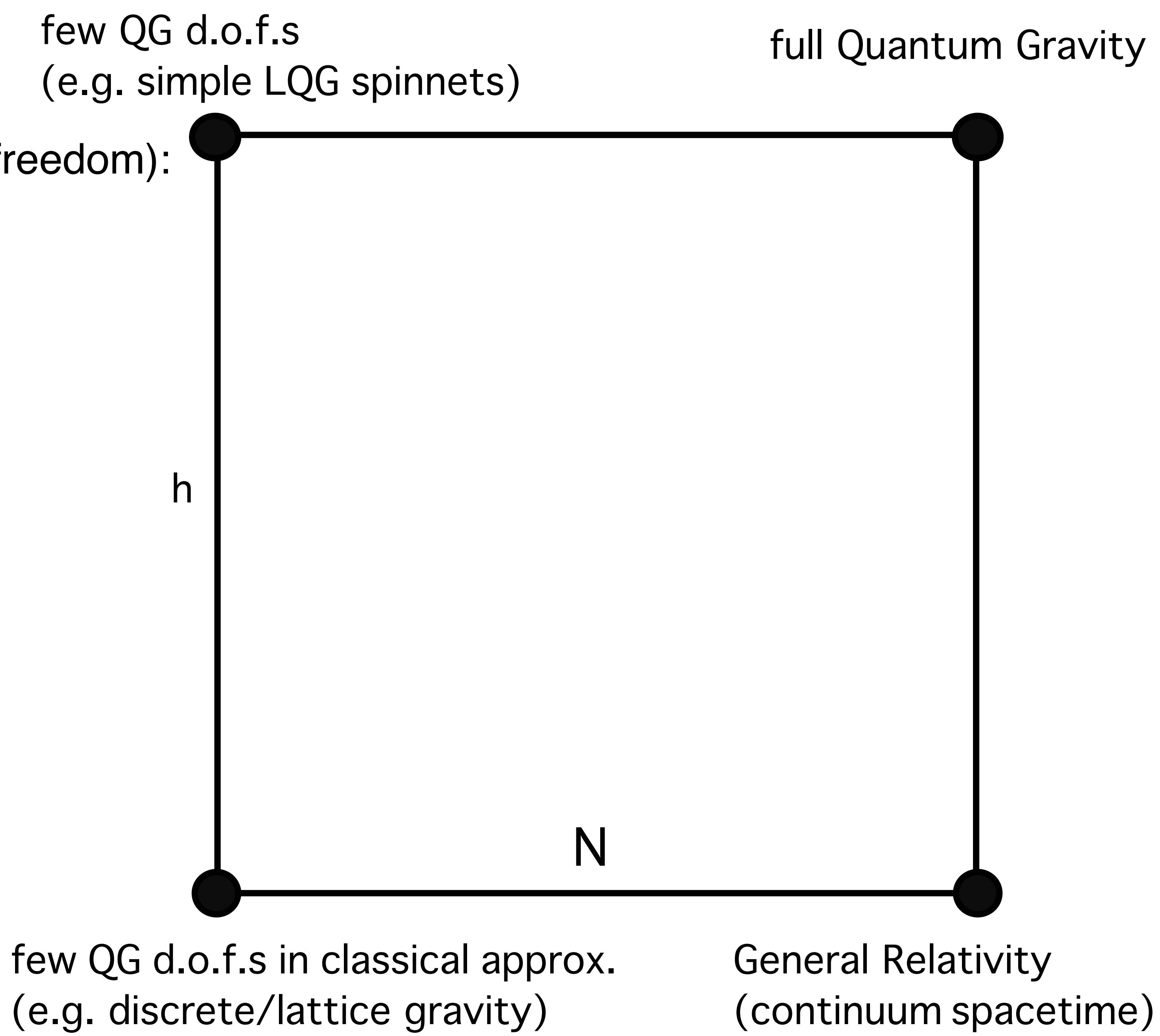

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“well-understood” in spin foam models

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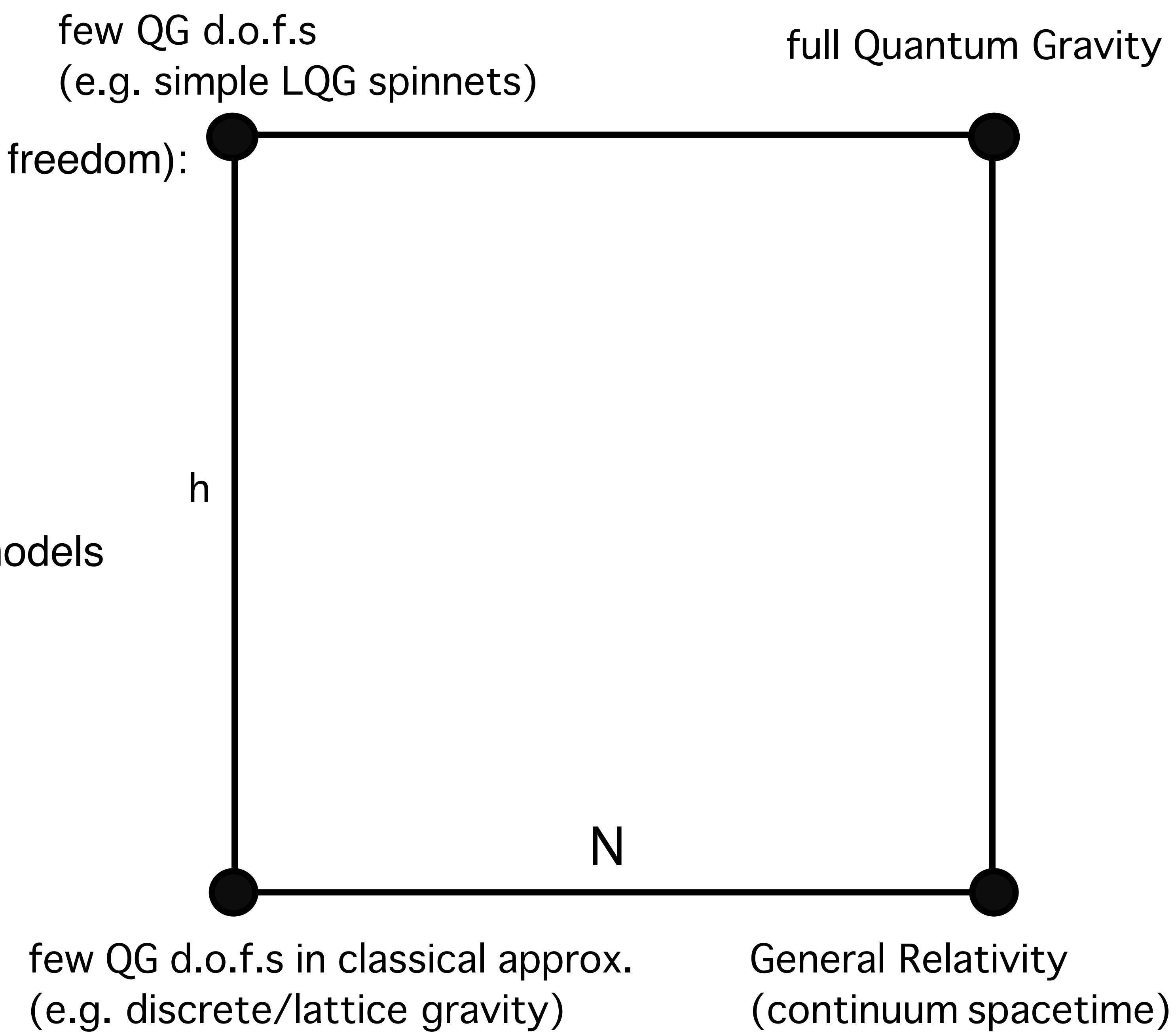

Problem of the continuum in QG: role of RG

Renormalization Group is crucial tool (mathematical, conceptual, physical)

renormalization is not about “curing or hiding divergences”, but
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- in specific GFT case:
- fundamental formulation of QG = QFT, defined perturbatively around "no-space" (degenerate) vacuum

- need to prove consistency of the theory: perturbative GFT renormalizability

- ned to understand effective dynamics at different "GFT scales":
RG flow of effective actions & phase structure & phase transitions

Geometrogenesis in LQG/GFT

idea of “geometrogenesis” in LQG/GFT :
starting from degenerate phase, continuum geometric physics in new phase
new phase can be “condensate” phase of QG “atoms of space”

in canonical LQG context:
T. Koslowski, 0709.3465 [gr-qc]

in covariant SF/GFT context:
DO, 0710.3276 [gr-qc]

also in tensor models
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natural hypothesis: very early Universe - big bang as QG phase transition

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- more specific hypothesis: continuum spacetime is GFT condensate

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- more specific hypothesis: continuum spacetime is GFT condensate
- GR-like dynamics from GFT condensate hydrodynamics

Geometrogenesis in LQG/GFT

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simple candidates for physical (geometric) vacuum: GFT condensates

what is their definition? do they have a continuum geometric interpretation?
what is their effective quantum dynamics? does it relate to GR?

DO, L. Sindoni, '10; S. Gielen, DO, L. Sindoni, 1303.3576 [gr-qc], 1311.1238 [gr-qc];
S. Gielen, '14; G. Calcagni, '14; L. Sindoni, '14; S. Gielen, DO, '14

Continuum Phases & phase transitions in LQG

canonical LQG:

purely kinematical, inequivalent representations (phases) of quantum algebra of observables

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AL vacuum $|0\rangle_{AL}$ → totally degenerate geometry (emptiest state)
connection highly fluctuating
diffeo invariant

$$_{AL}\langle 0|E_S|0\rangle_{AL} = 0 \quad \forall S$$

$$\delta_{AL}E_S << 1 \quad \delta_{AL}A_S >> 1$$

J. Lewandowski, A. Okolow, H. Sahlmannm T. Thiemann'06
C. Fleischack, '06

KS vacuum $|0\rangle_{KS}$ → non-degenerate geometry (triad condensate)
connection highly fluctuating
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$$_{KS}\langle 0|E_S|0\rangle_{KS} = E_S \quad \forall S$$

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T. Koslowski, H. Sahlmann, 1109.4688 [gr-qc]

DG vacuum
(or BF vacuum) $|0\rangle_{DG}$ → non-degenerate flat connection
metric highly fluctuating
diffeo covariant
simplicial context

$$_{DG}\langle 0|F(A)|0\rangle_{DG} = 0$$

$$\delta_{DG}A << 1 \quad \delta_{DG}E_S >> 1$$

B. Dittrich, M. Geiller, 1401.6441 [gr-qc]

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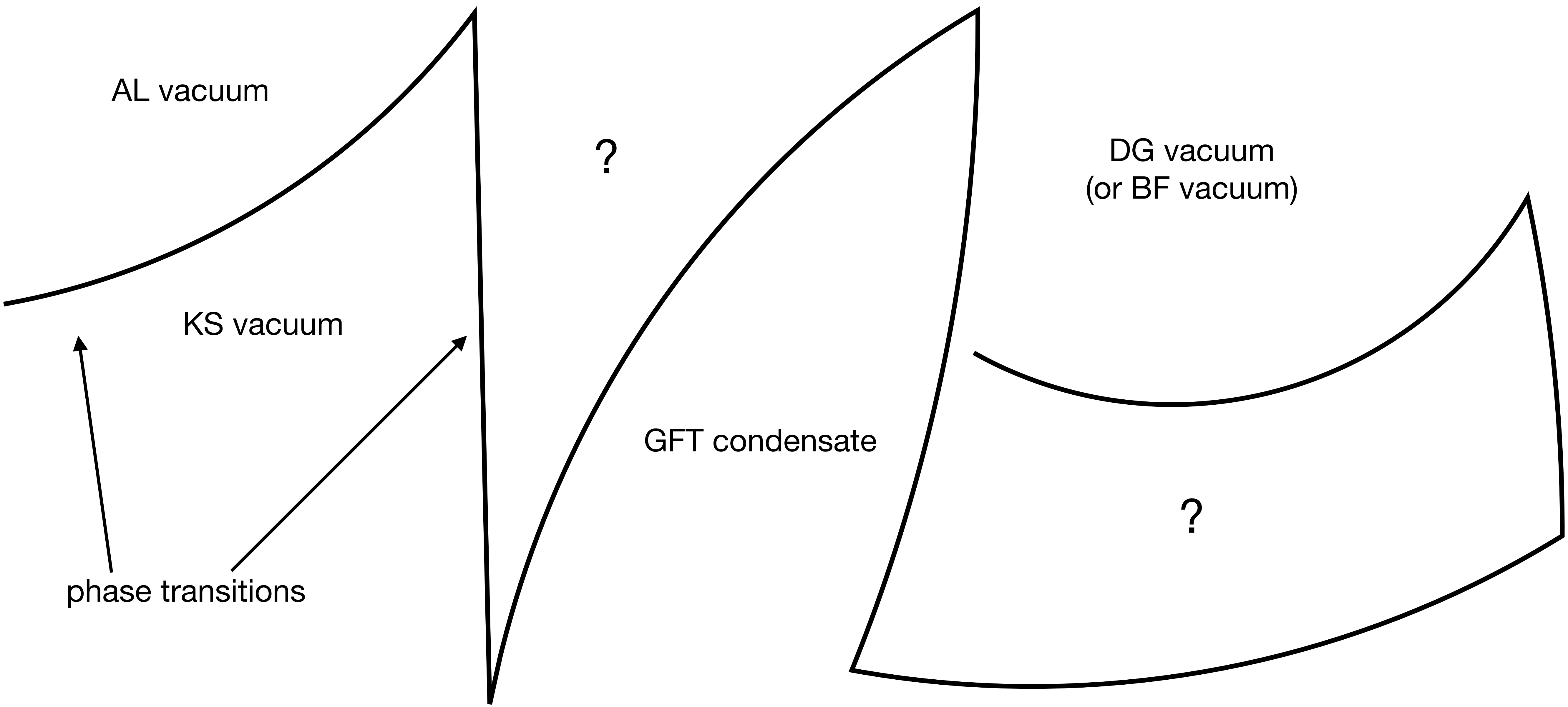

Continuum Phases & phase transitions in LQG

spin foam models (without GFT framework)

- rewrite them as lattice gauge theory path integrals
- define (background independent) coarse graining procedure
- look for flow of effective actions and fixed points

technically (numerically) very challenging

many results, mainly in simplified models (simpler algebraic data, dimensionally reduced models)

work by:

B. Bahr, B. Dittrich, F. Eckert, F. Hellmann, W. Kaminski, M. Martin-Benito, S. Steinhaus, …. - ’09-‘15

Renormalization of GFTs: where are we?

- power counting and radiative corrections in GFT models
  (cut-off of fields in representation space)

- topological simplicial GFT models (BF theory):
  - partial power counting and scaling theorems - large-N scaling

    L. Freidel, R. Gurau, DO, ’09; J. Magnen et al., ’09; J. Ben Geloun, J. Magnen, V. Rivasseau, ‘10 ; R. Gurau, ’11; S. Carrozza, DO, ’11,’12
  - radiative corrections of 2-point function: need for Laplacian kinetic term

    J. Ben Geloun, V. Bonzom, ‘11
  - super-renormalizability in abelian case (3d, with Laplacian)

    J. Ben Geloun, ‘13

- 4d gravity models
  - super-renormalizability of some versions of BC model

    A. Perez, C. Rovelli, ’00, ‘01
  - radiative corrections of 2-point function in EPRL-FK model

    T. Krajewski, J. Magnen, V. Rivasseau, A. Tanasa, P. Vitale, ’10; A. Riello, ‘13

Renormalization of GFTs: where are we?

- systematic renormalisation group analysis of tensorial GFT models:

  requires subtle analysis of combinatorics of diagrams (dual to cellular complexes)

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- Functional Renormalization Group for TGFTs

D. Benedetti, J. Ben Geloun, DO, '14; J. Ben Geloun, R.Martini, DO, '15

Renormalization group flow of GFTs from FRG

D. Benedetti, J. Ben Geloun, DO, ‘14

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an example: $\varphi(g_1, g_2, g_3) = \sum_{p_1,p_2,p_3} \varphi_{p_1p_2p_3} e^{ip_1\theta_1}\, e^{ip_2\theta_2} e^{ip_3\theta_3} \quad \in \mathbb{R} \qquad g_i = e^{i\theta_i} \in U(1) \quad \theta_i \in [-\pi, \pi) \quad p_i \in \mathbb{Z}$

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flow equations:

$$\partial_t \mu_N = -\mu_N \eta - \frac{\lambda_N\, N}{(N+\mu_N)^2}\left\{\frac{9}{2}(3N+2)(N+1) + \frac{\eta}{2}\Big(11 + 18N + 9N^2\Big)\right\}$$

$$\partial_t \lambda_N = -\frac{1}{3}\lambda_N^2 \frac{\eta}{(N+\mu_N)^3} N(3N+1)(6N+13) + 9\lambda_N^2 \frac{(\eta+1)}{(N+\mu_N)^3} N(N+1)(N+2) - \ldots$$

non-autonomous system (due to external scale a = size of grow manifold)

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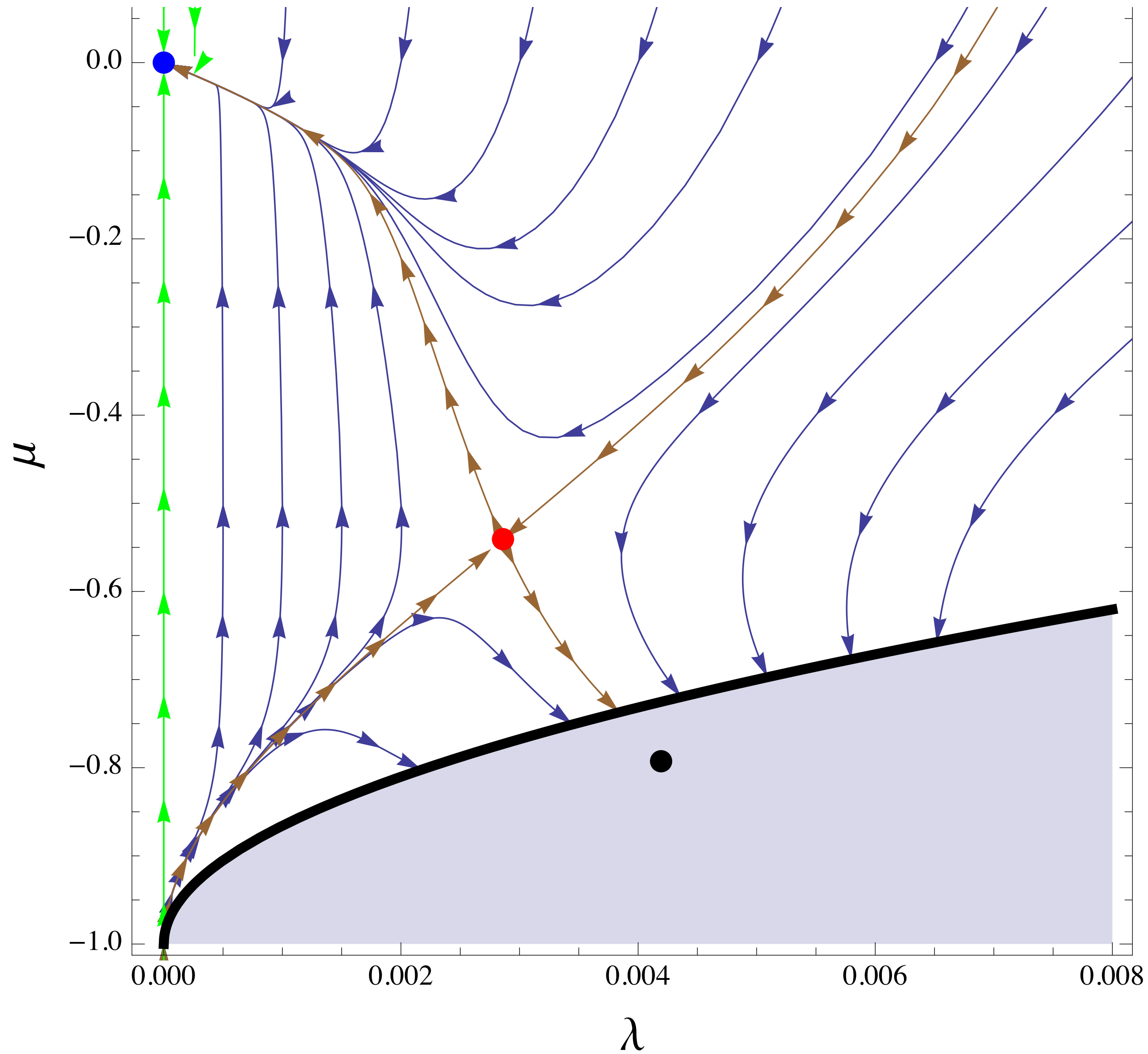
large-N regime ("formal UV"):



asymptotic freedom
(Gaussian fixed point with two relev. directions)

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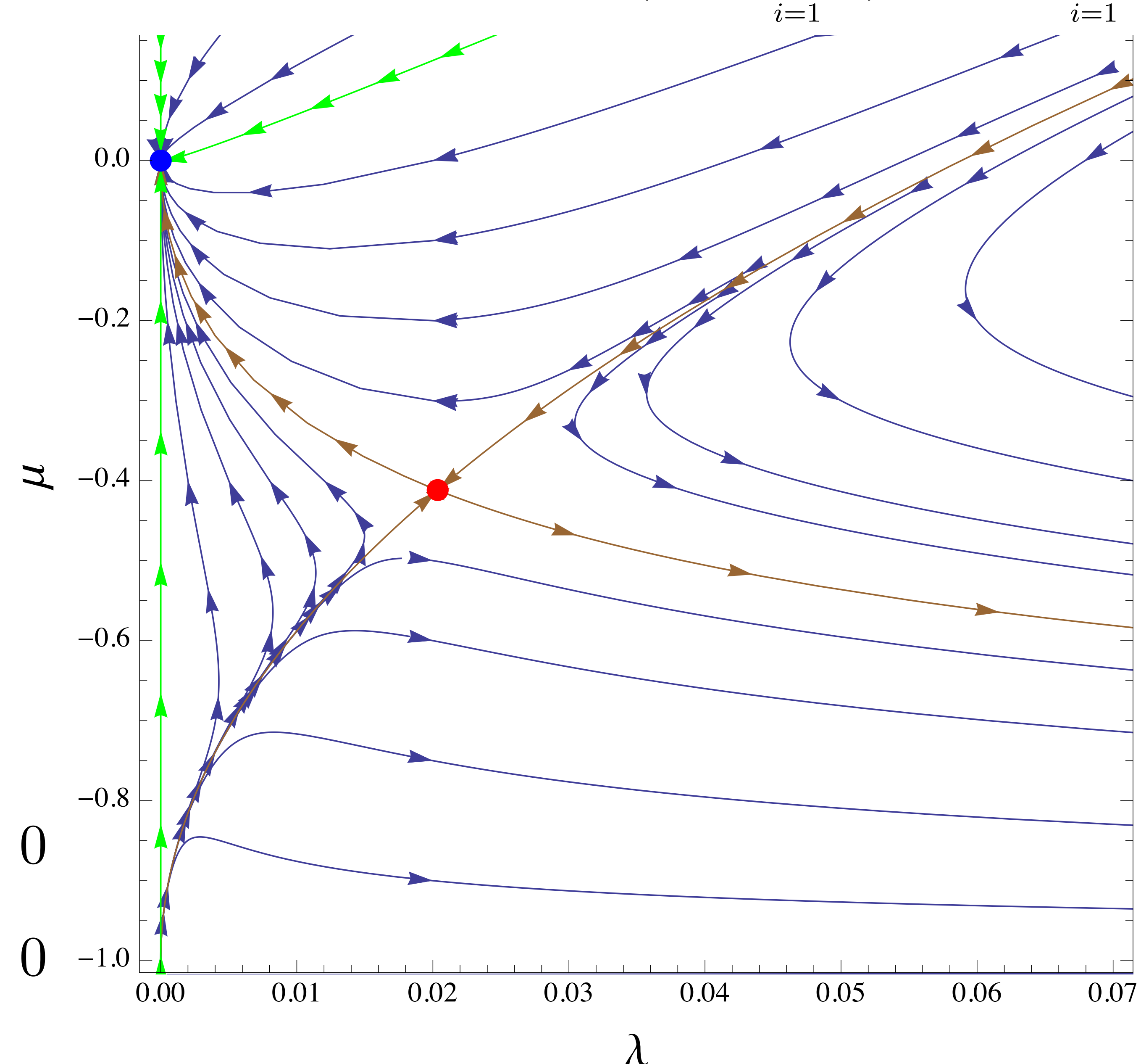
small-N regime ("formal IR"):

two IR fixed points:
Gaussian - 2 relevant directions
non-Gaussian - 1 rel., 1 irrel. directions

two phases:

"degenerate" $\mu > 0 \quad \langle\varphi\rangle = 0$

"condensate" $\mu < 0 \quad \langle\varphi\rangle \neq 0$



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2nd message

problem of the continuum in QG (GFT,LQG): crucial to connect to macrophysics, difficult and open

we are addressing it

RG is crucial tool, different strategies, many results (renormalizable models, RG flows,…)

QG phase transition (condensation?) could be physical

cosmological interpretation: realization of "Emergent Spacetime" and of "Universe as a Condensate" ideas

Quantum spacetime:
the difficult path from microstructure to cosmology

Quantum Gravity problem:
identify microscopic d.o.f. of quantum spacetime and their fundamental dynamics

derive effective (QG-inspired) models for fundamental (quantum) cosmology:
explain features of early Universe, obtain testable QG predictions

various models: loop quantum cosmology, ...

task is daunting (imagine analogue problem in condensed matter theory)

(Quantum) Cosmology from GFT

S. Gielen, DO, L. Sindoni, PRL, arXiv:1303.3576 [gr-qc]; JHEP, arXiv:1311.1238 [gr-qc]

problem 1:
identify quantum states in fundamental theory with continuum spacetime interpretation

problem 2:
extract from fundamental theory an effective macroscopic dynamics for such states

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QG (GFT) analogue of Gross-Pitaevskii hydrodynamic equation in BECs
is
non-linear and non-local extension of quantum cosmology equation for collective wave function

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following procedures of standard BEC

QG (GFT) analogue of Gross-Pitaevskii hydrodynamic equation in BECs
is
non-linear and non-local extension of quantum cosmology equation for collective wave function

similar equations obtained in non-linear extension of LQC (Bojowald et al. ’12)

GFT states and approximate continuum geometries

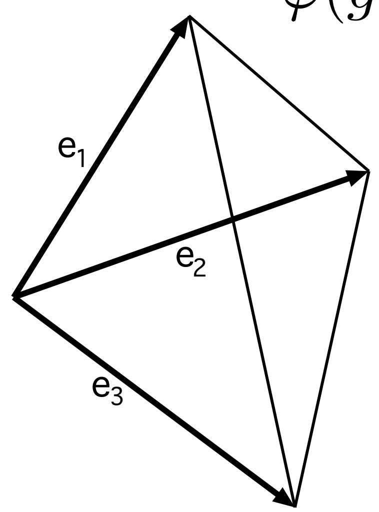
- work with GFT with simplicial geometric interpretation (Riemannian SO(4) case for simplicity)

$$\varphi(g_1, g_2, g_3, g_4) \leftrightarrow \varphi(B_1, B_2, B_3, B_4) \to \mathbb{C}$$

describes geometric tetrahedron

$$B_i^{AB} = \epsilon_i{}^{jk} e_j^A e_k^B$$

(closure + simplicity constraints)



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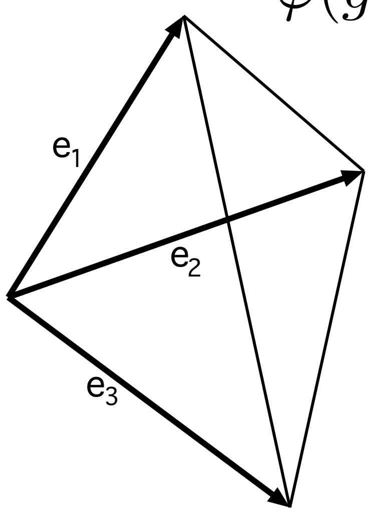

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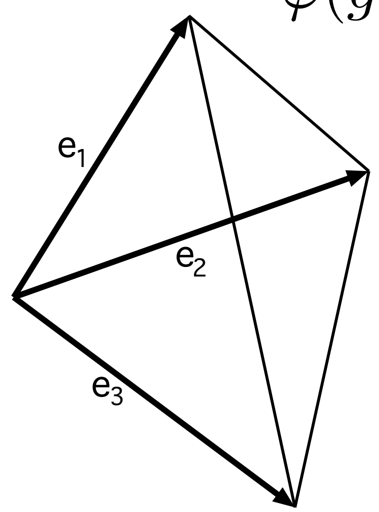

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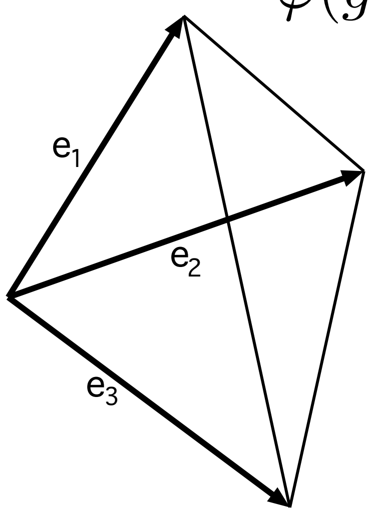

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interpretation: spatial metric coefficients (and conjugate variables) "sampled" at N points

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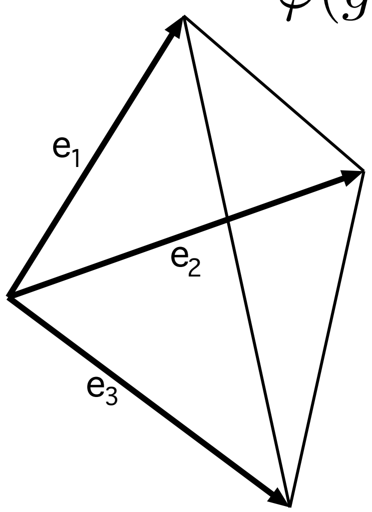

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- classical criterion for homogeneity (for GFT data):

$$g_{ij(m)} = g_{ij(k)} \quad \forall k, m = 1, \ldots, N$$

i.e. all GFT quanta are labelled by the same (gauge invariant) data

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similar constructions in LQG (Alesci, Cianfrani) and LQC (Bojowald, Wilson-Ewing, …..)

Quantum GFT condensates

a simple choice of quantum GFT condensate
(homogeneous continuum quantum space)

other constructions possible, depending on how much information the condensate state has to encode (in a coarse-grained form)
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- data for homogeneous anisotropic geometries
- truly non-perturbative quantum states (infinite QG dofs, superposition of graphs)
- support perturbations at any sampling scale N
- 2nd quantized coherent states $\hat{\varphi}(g_I)|\sigma\rangle = \sigma(g_I)\,|\sigma\rangle$
- can be studied using BEC techniques

Effective cosmological dynamics from GFT

follow closely procedure used in real BECs

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applied to (coherent) GFT condensate state,
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$$\int [dg_i'] \, \tilde{\mathcal{K}}(g_i, g_i')\sigma(g_i') + \lambda \frac{\delta \tilde{\mathcal{V}}}{\delta\varphi(g_i)}|_{\varphi\equiv\sigma} = 0$$

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effective cosmological dynamics from full-blown 4d gravity models? under way (DO, L. Sindoni, E. Wilson-Ewing, '15)

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macroscopic geometric conjugate variables are instead:

$$(\vec{\Pi}[g_a]^{\mathrm{av.}}) = \langle\hat{\Pi}[g_a]\rangle / \langle\hat{N}\rangle$$

"average holonomy"

one extensive, other intensive

$$B^i_a = \langle\, \widehat{b^i_a}\,\rangle$$

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two immediate (generic) consequences:

1) GFT condensate cosmology gives quantum corrections to cosmological equations akin to LQC ones

2) effective cosmological equations will carry a dependence on <N> (purely quantum observable) when expressed in terms of cosmological variables

exact relation between <N> and cosmological variables depends on quantum state

3rd message(s):

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derivation of (quantum) cosmological equations from GFT quantum dynamics very general
it rests on:

- continuum homogeneous quantum space (at microscopic scales) ~ GFT condensate
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non-linear quantum cosmology is QG analogue of Gross-Pitaevskii hydrodynamics for BECs

consistent with "geometrogenesis" hypothesis and general "macro-from-micro" scenario

GFT condensate cosmology: phenomenology?

"standard" directions
(but calculations to be done):

phenomenology as in LQC, here derived from fundamental theory

basis for most LQC phenomenology: modified Friedmann equation
plus quantum corrections

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- diffeos in GFT also expected to be deformed: A. Baratin, F. Girelli, DO, '11
  - simplicial diffeos realised as global quantum group symmetry in topological models
  - expect more surprises at effective cosmological level

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exactly as one would do in a BEC….

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(but conceptual and technical issues to be solved, first)

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from first principles, i.e. from full QG formalism

needed for computation of CMB spectrum
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expect deformation of standard QFT:

- holonomization of the connection and non-commutativity of triad variables, both entering definition of basic variables for perturbations (momenta, positions)

- derivation of effective dynamics of perturbations around mean field in topological GFT:
non-commutative scalar field theory on non-commutative flat space
W. Fairbairn, E. Livine, '07; F. Girelli, E. Livine, DO, '09

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a new avenue for analogue gravity: analogue GFT condensate quantum cosmology in real BECs?

need to simulate mini-superspace, not spacetime
BEC hydrodynamics needs to reproduce GFT "classical" equations", not GR equations
no problem with lack of diffeo invariance or relativistic symmetry in the lab

Foundational issues: the universe as a (quantum) fluid

- GFT condensates encoded in “collective wave function” identical to Quantum Cosmology one
- corresponding dynamical equation is non-linear and non-local (on mini-superspace)
- cosmological dynamics is hydrodynamics of fundamental GFT (analogue of GP equation for BEC)
- still, fundamental dynamics is (more or less) standard quantum mechanics for QG d.o.f.s (although big interpretational issues (e.g. concerning probabilities, unitarity, etc) remain)

calls for new interpretation of “quantum cosmology” (see also Bojowald, ’15):

- quantum cosmology is not quantum at all; rather, “cosmological hydrodynamics” no probability for “the whole universe”, no “Hilbert space of states of the Universe”
- can still use expectation values (average quantities) but in “hydrodynamics” (realistic/statistical) sense
- no problem of “collapse of cosmological wave function” or spontaneous collapse due to non-linearites?

related work by Pearle, Sudarsky, Perez, Peter, Martin, ...

4th message

a new promising direction to extract effective cosmological dynamics
(and associated phenomenology)

directly from full QG theory!

Thank you for your attention!