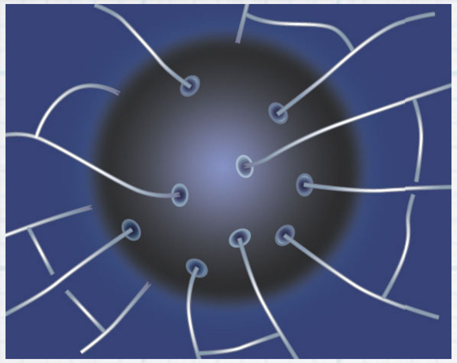
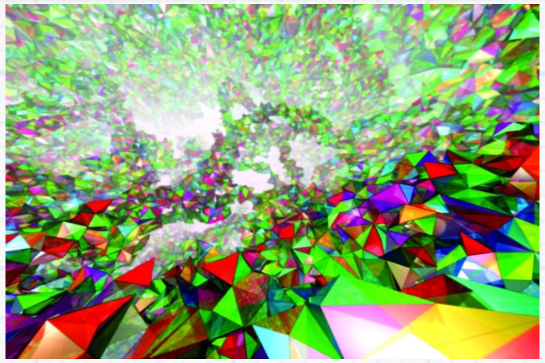
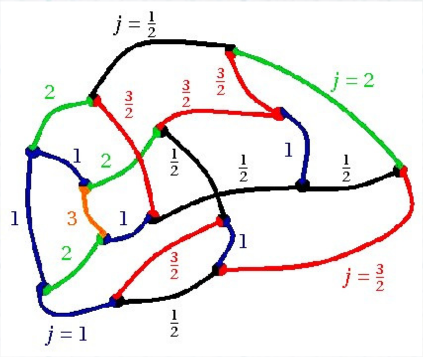
  

Loop Quantum Gravity & Spinfoams: an Overview

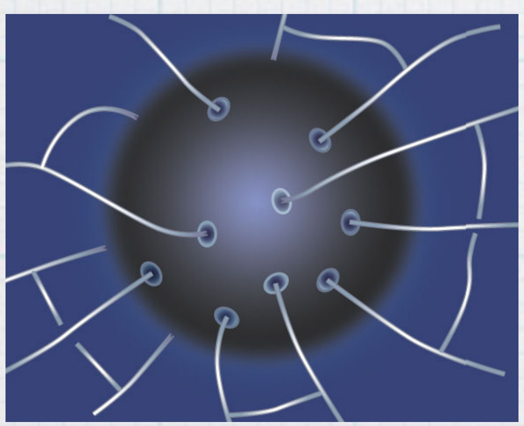
Etera Livine

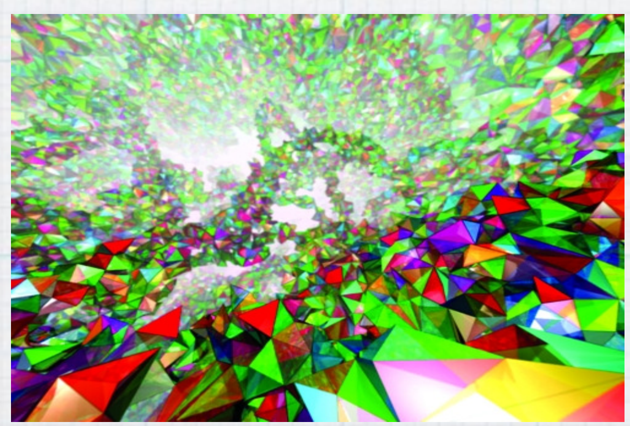
Laboratoire de Physique LP ENSL & CNRS

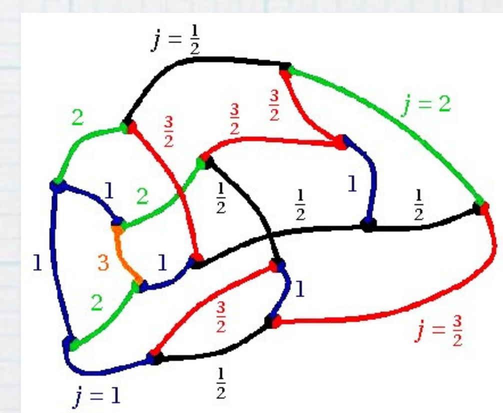
CEA Saclay - March '17

(Loop) Quantum Gravity

1. What is Quantum Gravity about?
2. Loop Quantum Gravity 1.0.1
3. Spinfoam Path Integrals
4. Applications and Phenomenology







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1. What is Quantum Gravity about?
   - Why Quantum Gravity?
   - The Basic Ingredients: what to expect?
   - Loop Quantum Gravity in a Nutshell
   - A Panorama of QG Approaches

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- General Relativity as a Gauge Field Theory
- Spin Network States for Quantum Geometry
- Discreteness of Space-Time ?!?
- Implementing the Dynamics

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   - Evolving Histories of Spin Networks
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- Loop Quantum Cosmology
- Quantum Black Holes
- Particle Physics: Non-Commutative Geometry

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Quantum Gravity

Why Quantum Gravity?

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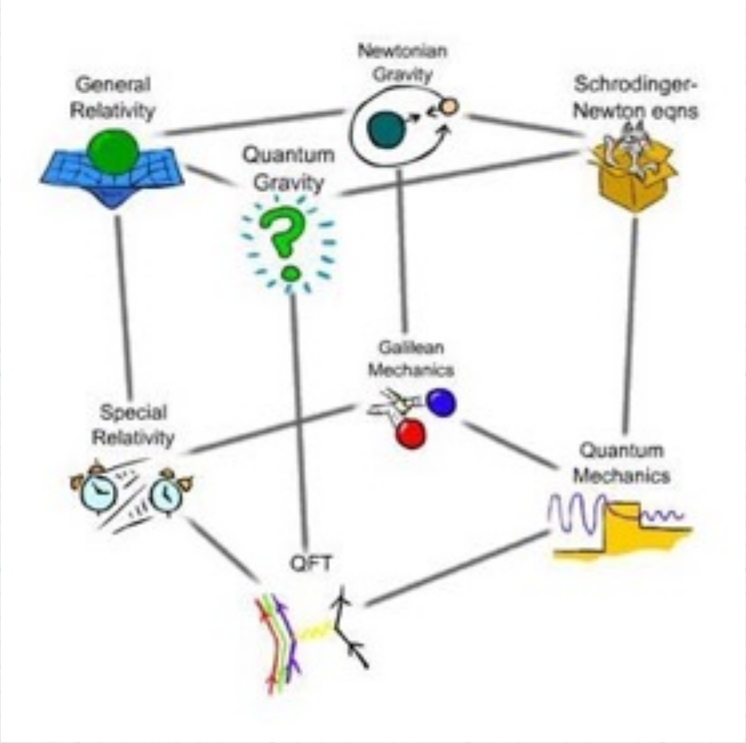
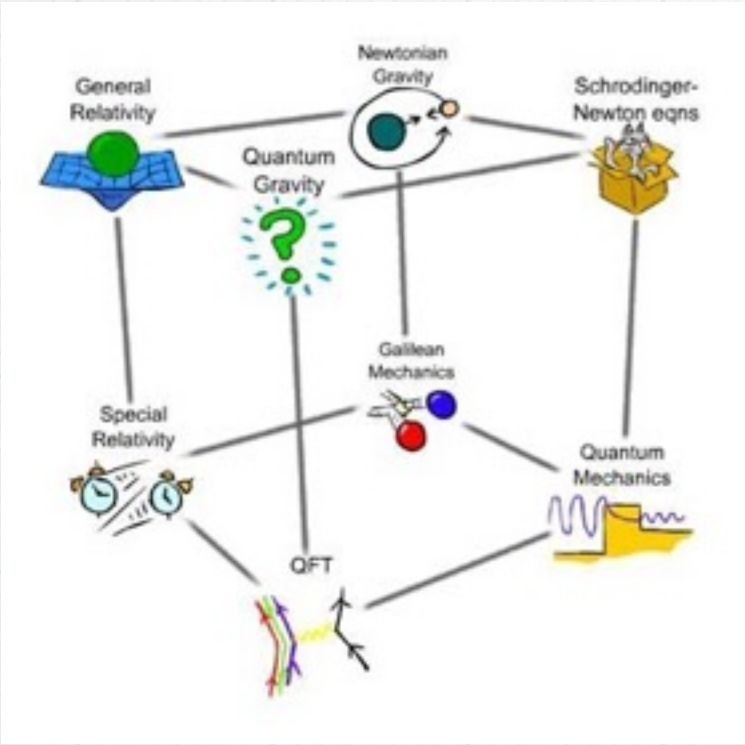


Consistent universal theory with $c, G_N, \hbar$

- No infinite resolution; the BH argument
- Non-renormalisability of GR as QFT
- Equivalence Matter $\leftrightarrow$ Geometry
- Solve GR singularities ?

Quantum Gravity

Why Quantum Gravity?



Consistent universal theory with $c, G_N, \hbar$

- No infinite resolution; the BH argument
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- Solve GR singularities ?

But also: how fundamental is QM? thermodynamics origin of GR? ...

Understand better the Structure of Space-Time !

What to expect from Quantum Gravity?

Quantum Gravity

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top-down
vs.
bottom-up

fundamental principles
vs.
effective perturbative formalism

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- Define observables, measurables
- New meaning of « Geometry »
- A new relativity principle and definition of observers
- Revisiting foundations of QM
- Universal « UV » completion of QFTs

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- Revisiting foundations of QM
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→ Better understanding of length and energy and renormalization

One-slide Loop Quantum Gravity

What is Loop Quantum Gravity?

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What is Loop Quantum Gravity?

a non-perturbative quantization of GR

One-slide Loop Quantum Gravity

What is Loop Quantum Gravity?

a non-perturbative quantization of GR

A « simple » plan to quantum gravity :

We try to quantize GR as well as we can,

We see what new structures we get,

We understand the limitations of quantization procedure,

We have a glimpse of what's beyond, of new principles

One-slide Loop Quantum Gravity

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a non-perturbative quantization of GR

- Background independent and Diffeo invariant

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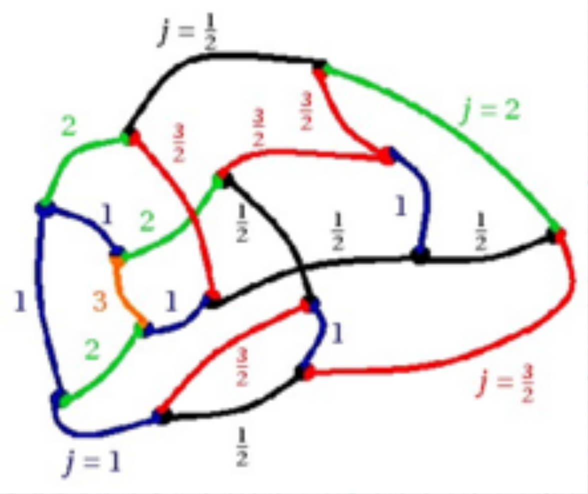

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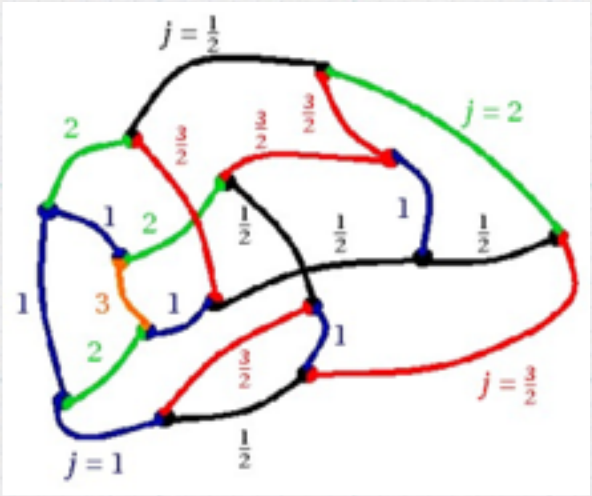

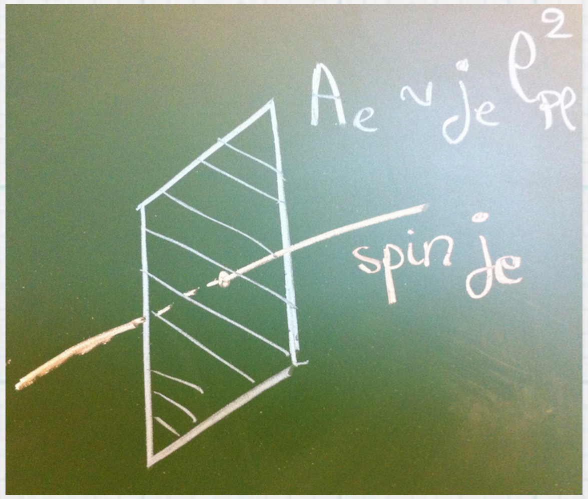

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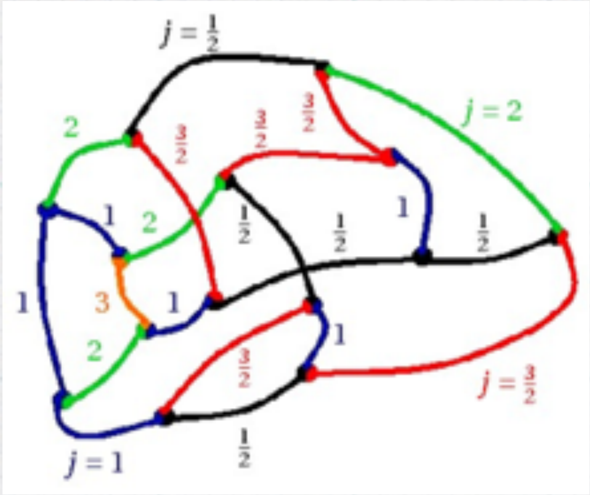

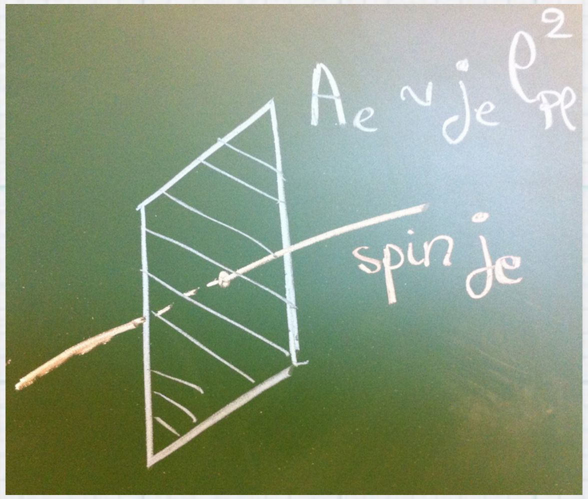

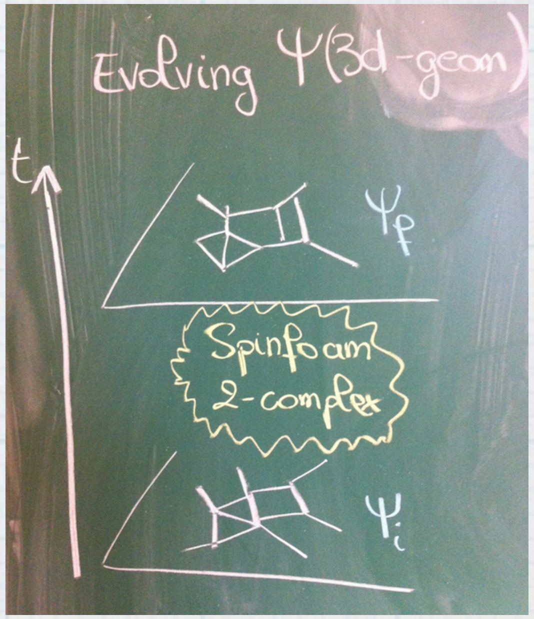

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Framework ready to discuss:

- quantum black hole dynamics, Planck scale phenomenology
- bulk reconstruction for boundary data, gravity/CFT dualities, ...

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Framework ready to discuss:

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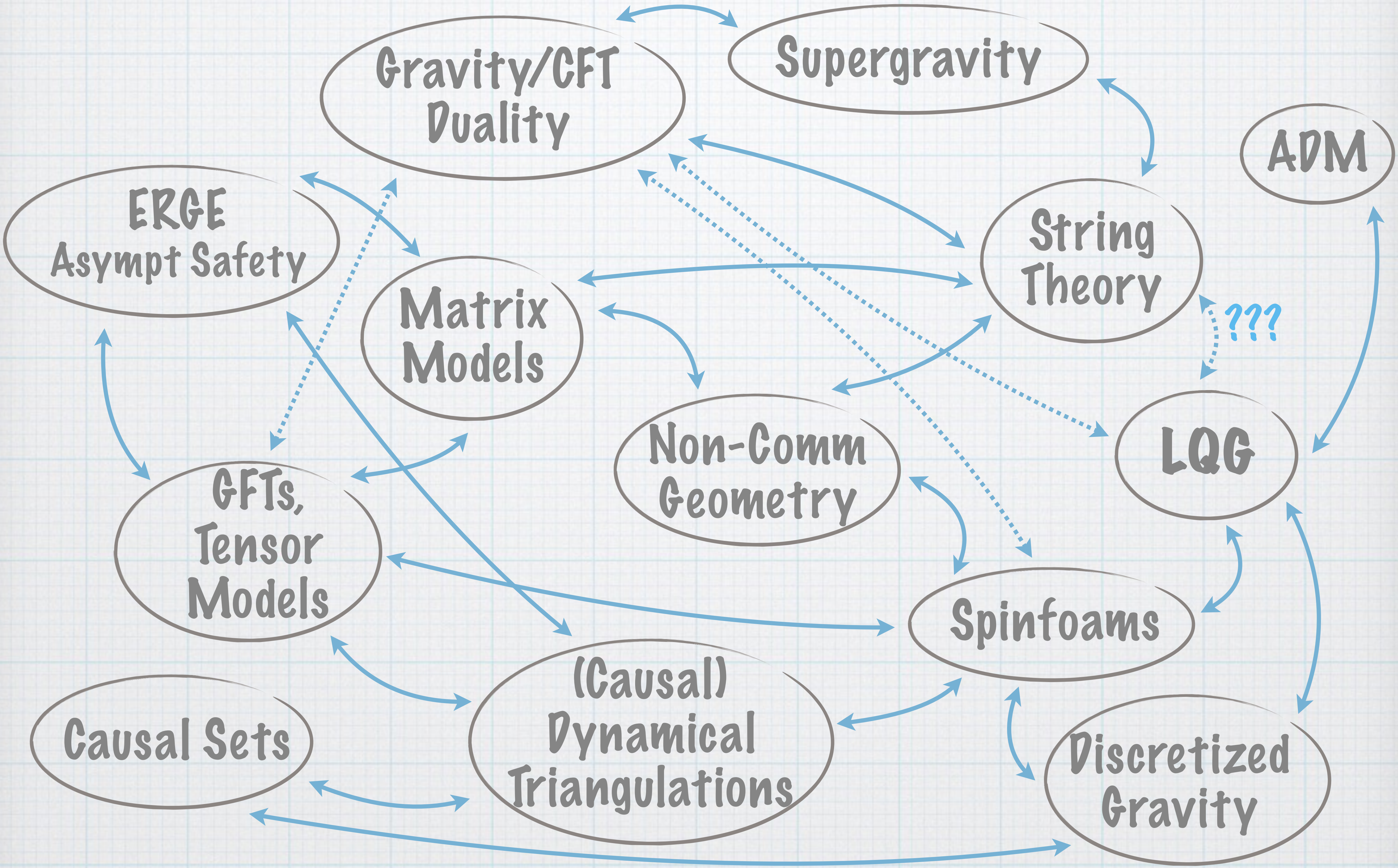
But... hard to connect to perturbative QFT

& compute effective QG corrections

LQG on the Map (without phenomenology)



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General Relativity as a Gauge Field Theory

The metric is not a fundamental field, it will emerge from other degrees of freedom describing the (quantum) geometry

Start with Palatini action with tetrad and Lorentz connection:

$$S[e^I_\mu, \omega^{IJ}_\mu] = \int_{\mathcal{M}} \epsilon_{IJKL} e^I \wedge e^J \wedge F^{KL}[\omega]$$

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Now proceed to 3+1 splitting and canonical analysis

General Relativity as a Gauge Field Theory

GR as constrained Hamiltonian system, with action:

$$S[E,A] = \int dt \int_\Sigma d^3x \, A^i_a \partial_t E^i_a - H$$

$$H = \Lambda_i \mathcal{G}^i + N^a \mathcal{H}_a + N\mathcal{H}$$

Canonical pair of Ashtekar variables living on space hypersurface:

- Triad field E^i_a giving 3d metric $h_{ab} = E^i_a E_{ib}$
- Ashtekar-Barbero SU(2) connection $A^i_a = \Gamma[E]^i_a + \gamma K^i_a$

Phase Space: $\{K, E\} = \delta^{(3)}$ $\{A, E\} = \gamma\delta^{(3)}$

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First-class Constraints:

- « Gauss law » constraints $\mathcal{G}^i$ generating SU(2) Gauge invariance
- Vector and Scalar constraints $\mathcal{H}_a, \mathcal{H}$ generating space-time diffeomorphisms

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No torsion

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Counting of d.o.f.s: $2 \times (3 \times 3) - 2 \times (3 + 4)$

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Gravitational Waves

General Relativity as a Gauge Field Theory

GR with the same phase space that SU(2) Yang-Mills !

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But diffeo constraint instead of $E^2 + F^2$ as Hamiltonian

General Relativity as a Gauge Field Theory

GR with the same phase space that SU(2) Yang-Mills ...

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And Immirzi parameter γ

- canonical transformation
- similar to θ parameter in QCD (Nieh-Yan invariant)
- as coupling for torsion if we include fermions
- controls CP violations in LQG
- $\gamma = \pm i$ is (anti-)self dual Lorentz connection

Loop Quantization

- Choose polarization: **wave-functions** $\Psi[A]$
- Choose **algebra of observables** to promote to operators

Holonomies $$U_c[A] = \mathcal{P}e^{\int_c ds\, A_a^i \tau_i \dot{c}^a} \qquad \in \mathrm{SU}(2)$$

and Flux $$\int_{\mathcal{S}} \epsilon^{abc} E_a^i \, dx_b \wedge dx_c \qquad \in \mathfrak{su}(2)$$

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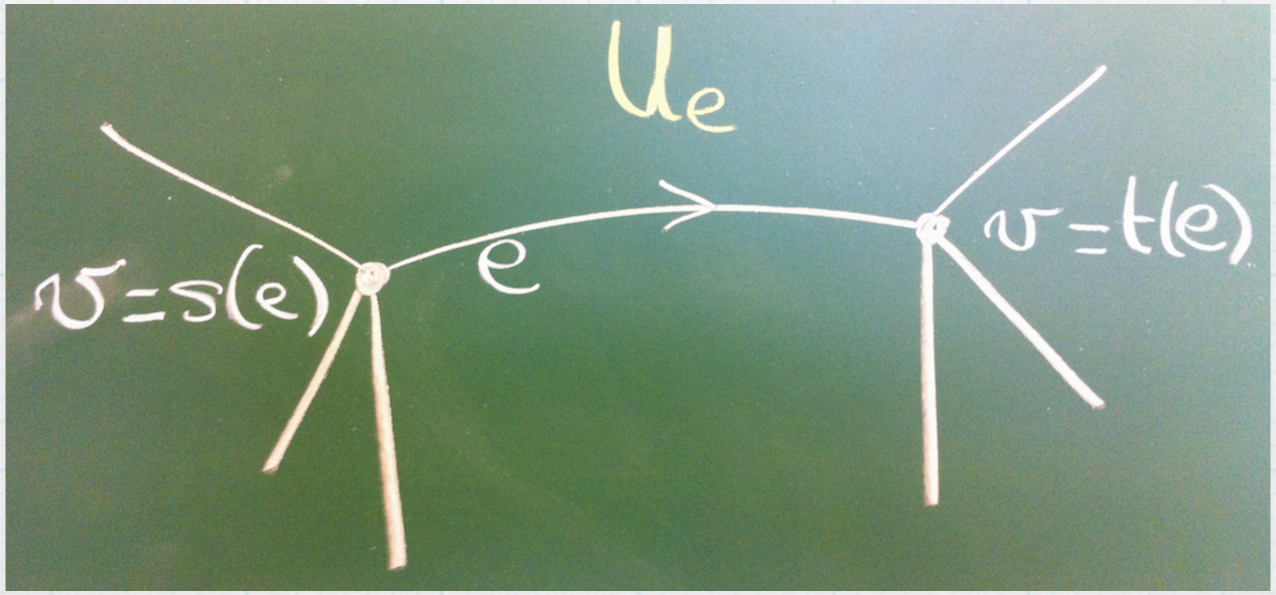
- **Study Dynamics given by Time Diffeomorphisms**

Spin Network States

Define Wave-functions of Holonomies along edge of Graph Γ

$$\Psi_\Gamma\left(\{U_e[A]\}_{e\in\Gamma}\right)$$



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& Impose SU(2) Gauge Invariance at graph vertices:

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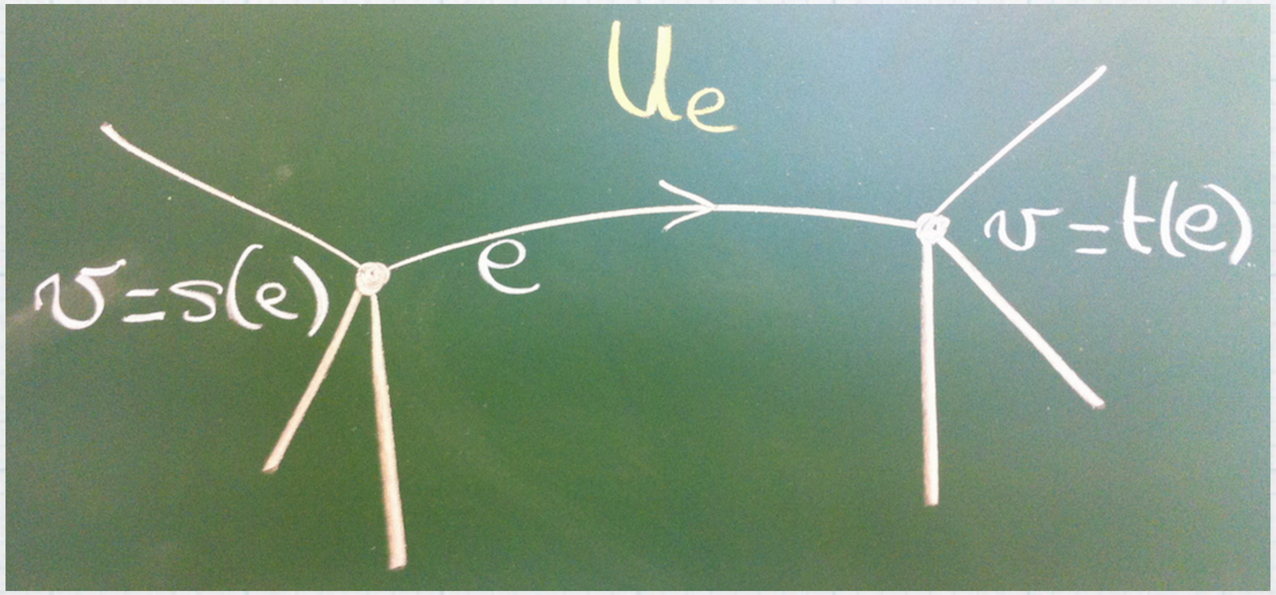

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- Then consider equivalence class of graphs under Diffeos
- Sum over all possible graphs by projective limit

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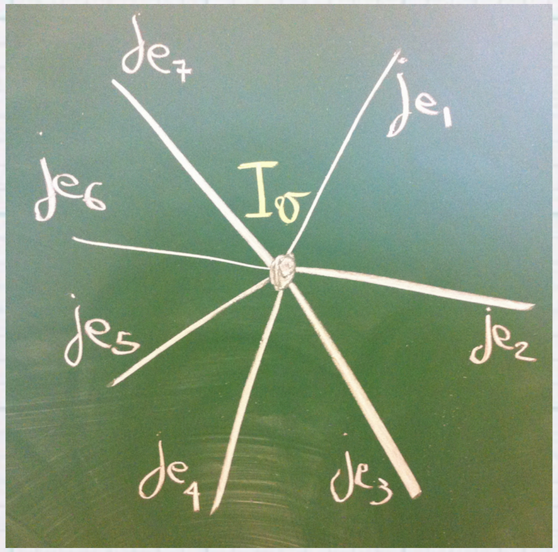
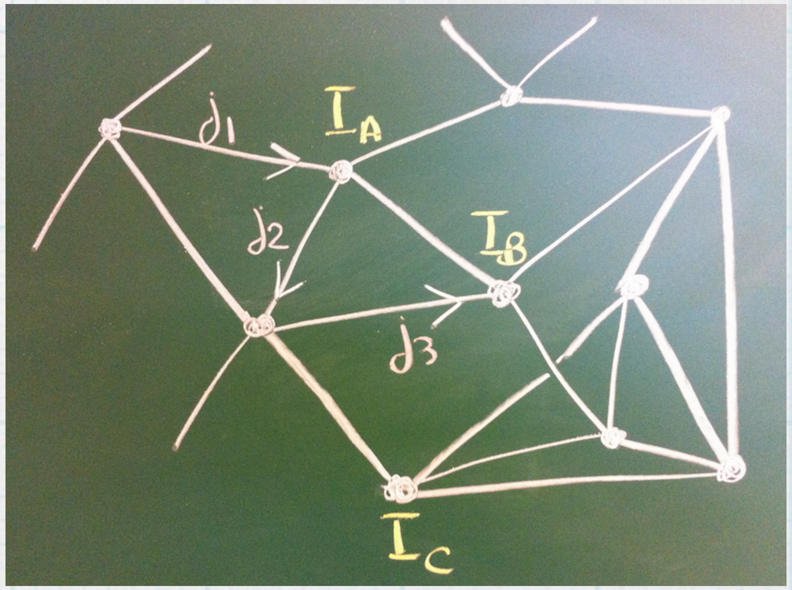
Basis given by Spin network states

- SU(2) representation on edges $j_e \in \mathbb{N}/2$
- Intertwiners around vertices

(Singlet state in tensor product)





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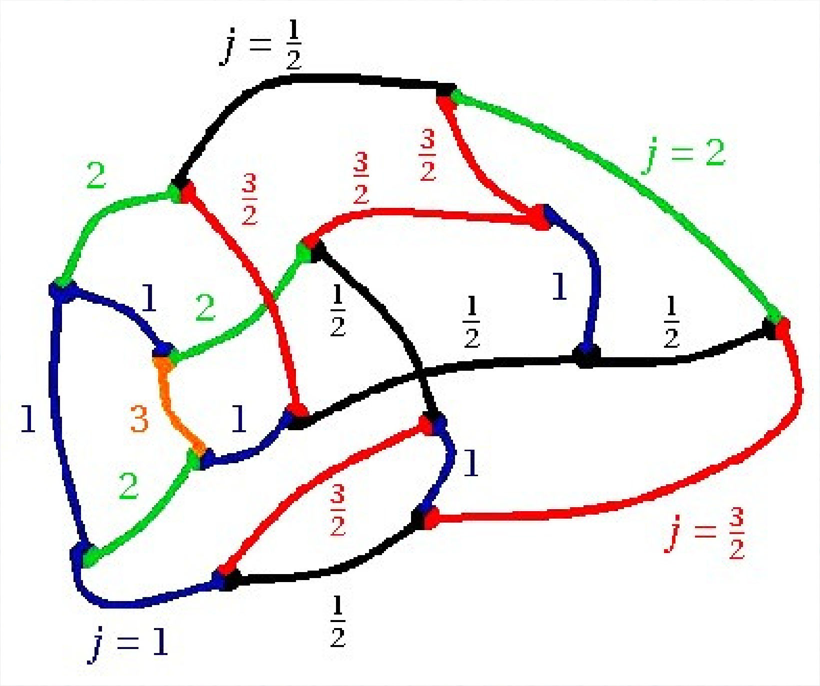
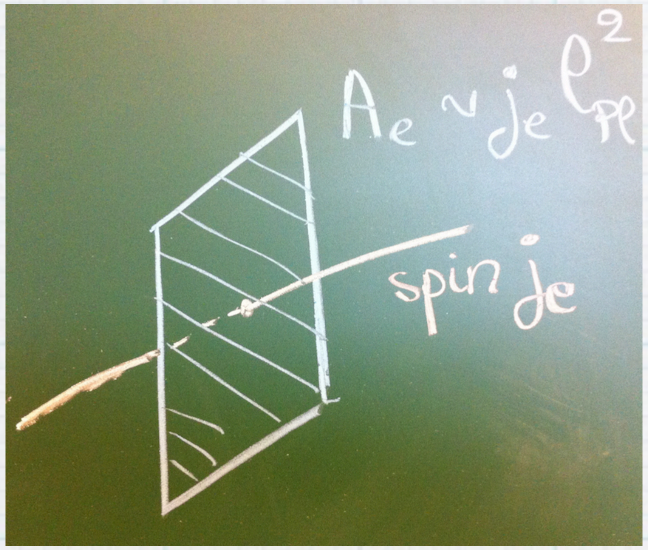
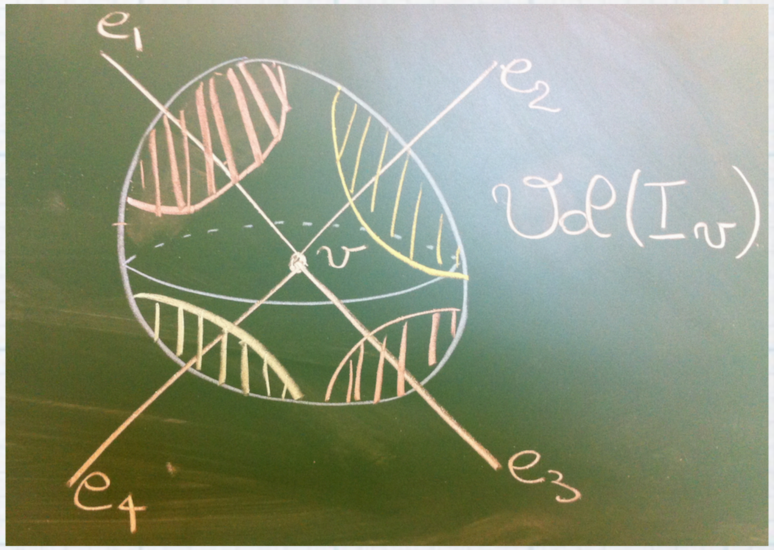


The Geometry of Spin Networks

Area and Volume becomes Quantum Operators

- Area given by spin on edges
- Volume determined by intertwiner at vertices





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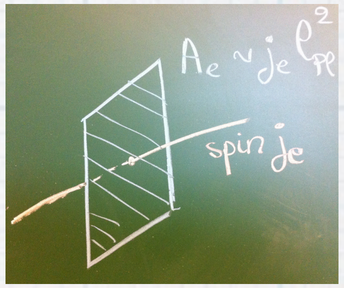

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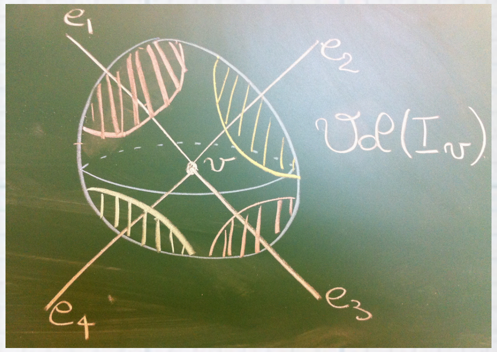

Spin network states as Quantum Discrete Geometries

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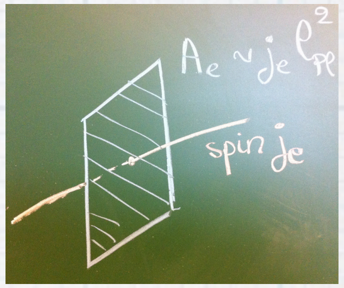

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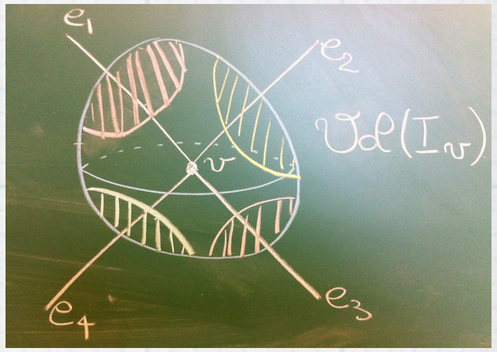
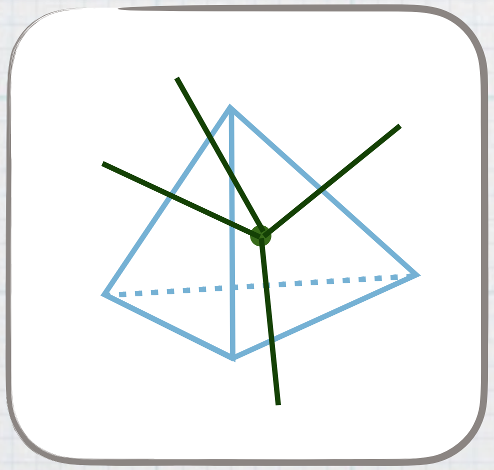
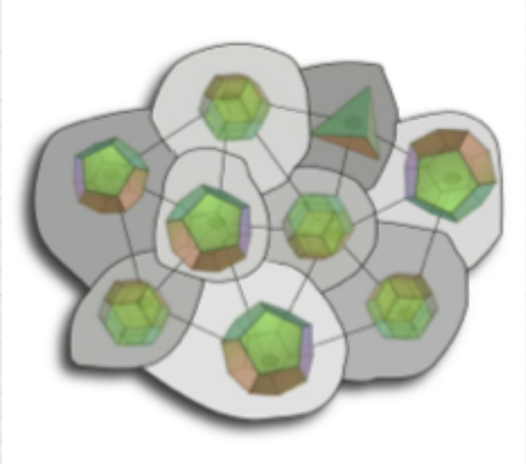


Spin network states as Quantum Discrete Geometries

- Twisted Geometries, extending Regge geometries
- Torsion of connection comes from Extrinsic Curvature !





Chunks of volume glued
without face matching
(only area matching)

The Geometry of Spin Networks

So we have a discreteness of space(-time) ...

Discrete geometry at Planck scale is expected in QG

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Two sources of discreteness:

- States built on Graphs

  but evolution and superposition of graphs

- Discrete area spectrum

  perfect to account for black hole entropy

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Discrete geometry at Planck scale is expected in QG

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  perfect to account for black hole entropy

But compatible with known physics? with Lorentz invariance?

but also area, length,.. are operators. No problem with rotations or boosts.

Hints to wards non-commutative geometry with deformed Poincaré symmetry

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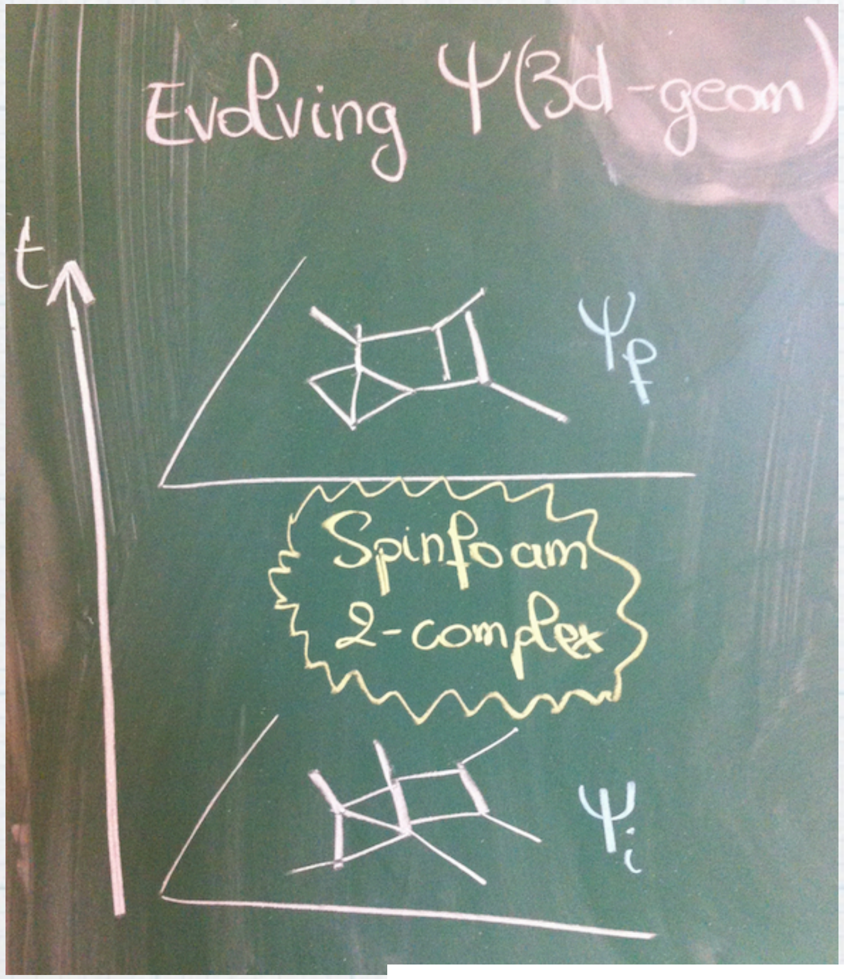

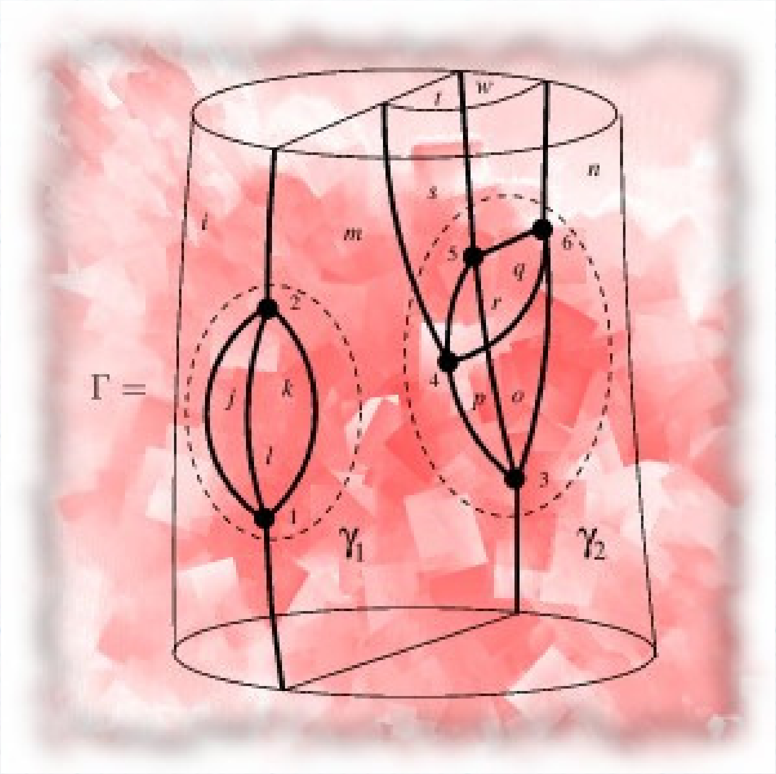

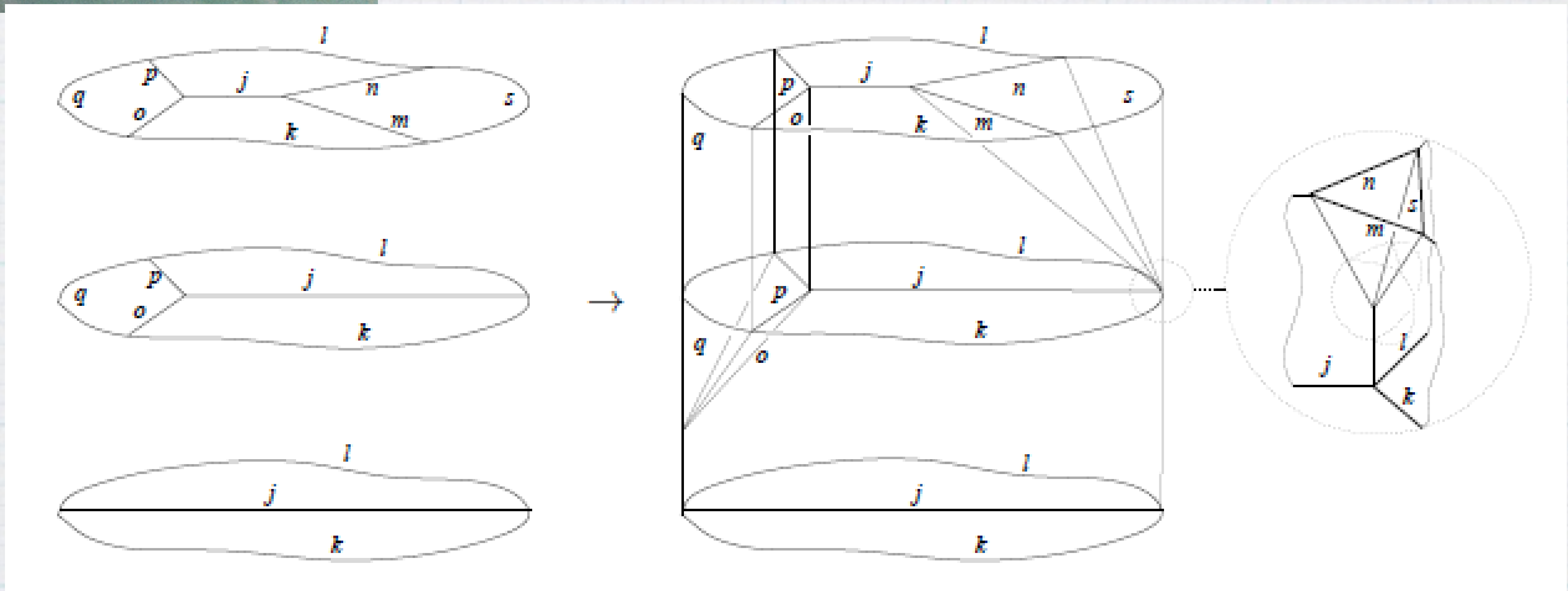

Evolving Spin Networks

Spinfoams as Histories of Spin Networks

- Spin on graph links
- Intertwiner on nodes

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topological dual ↓

- Spin for areas
- Intertwiner for volumes

Evolving Spin Networks

Spinfoams as Histories of Spin Networks

time

- Spin on graph links
- Intertwiner on nodes

→

- Spin on spinfoam faces
- Intertwiner on edges
- Amplitude at spinfoam vertex

topological dual ↓

- Spin for areas
- Intertwiner for volumes

→

- Spin for areas
- Intertwiner for volumes
- Amplitude for 4d-cells

Evolving Spin Networks

Spinfoams as Histories of Spin Networks

time

- Spin on graph links
- Intertwiner on nodes

→

- Spin on spinfoam faces
- Intertwiner on edges
- Amplitude at spinfoam vertex

topological dual

- Spin for areas
- Intertwiner for volumes

→

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- Intertwiner for volumes
- Amplitude for 4d-cells

SpaceTime Event
as Spinfoam Vertex

State-Sum Models

Local Ansatz for Spinfoam Amplitude:

$$\mathcal{A}_\Delta[j_\partial, \mathcal{I}_\partial] = \sum_{\{j_f, \mathcal{I}\}} \prod_f d^\nu_{j_f} \prod_e \mathcal{A}_e[j_{f\ni e}, \mathcal{I}_e] \prod_v \mathcal{W}_v[j_{f\ni v}, \mathcal{I}_{e\ni v}]$$

- Face and edge amplitudes are measure factors
- Vertex amplitude contain all the dynamics
- Defines transition amplitude between initial and final states
- But also allows for arbitrary boundary/bulk topology

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- But also allows for arbitrary boundary/bulk topology

Can derive $\mathcal{W}_v$ from Hamiltonian constraint,
but better to define it from TQFT discretized path integral

Spinfoam Models from TQFT

Topological field theory has no local d.o.f. :
path integral can be discretized with no information loss

3d gravity is exactly topological

$$S[A,e]=\int_{\mathcal{M}}\mathrm{Tr}\, e\wedge F[A]+\Lambda e\wedge e\wedge e$$

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4d gravity is « almost-topological »

$$S[A,e] = \int_{\mathcal{M}} \mathrm{Tr}\, *(e \wedge e) \wedge F[A] + \Lambda e \wedge e \wedge e \wedge e$$

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$$S[A,B,\phi]=\int_{\mathcal{M}}\mathrm{Tr}\, B\wedge F[A]+\phi B\wedge B$$

simplicity constraints

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- Crane-Yetter for BF theory
- EPRL model for 4d gravity

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Spinfoam Path integral for QG as Constrained BF Theory

- Path integral of discretized Lagrangian for discretized fields
- Large Spin asymptotics lead back to Regge calculus
- « Graviton propagator » as spin-spin correlation gives back $1/r^2$ Newton law (plus corrections)

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- Should define projector onto Hamiltonian constraints
- Should lead back to GR in coarse-grained large scale limit

Spinfoam Models: The Ponzano-Regge model

3d quantum gravity given by Ponzano-Regge path integral :

- 3d bulk triangulations or dual 2-complex
- Spins on edges j_e
- Amplitude as product of 6j-symbols

$$\mathcal{A}_\Delta = \sum_{\{j_e\}} \prod_e (2j_e + 1) \prod_T \{6j\}$$

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Topological Invariance

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Topological Invariance

solve Hamiltonian constraints

Spinfoam Amplitudes as Feynman Diagrams

Back to Matrix Models: consider matrices of size N

$$S[M] = \frac{1}{2}\mathrm{Tr}M^2 - \lambda \mathrm{Tr}M^3$$

We expand the path integral in Feynman diagrams:

$$Z = \int [dM] e^{-S[M]} = \sum_n \frac{\lambda^n}{n!} \int [dM] \left(\mathrm{Tr}M^3\right)^n e^{\frac{1}{2}\mathrm{Tr}M^2}$$

$$= \sum_{g\in\mathbb{N}} \sum_V \lambda^V N^{2-2g} \mathcal{N}_g(V)$$

It expands as a sum over 2d triangulations !

Large N expansion, double scaling limit, continuum limit, can include all polygon interactions, mapping to CFTs ...

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Identify field theory that generate spinfoam amplitudes as Feynman diagrams

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Identify field theory that generate spinfoam amplitudes as Feynman diagrams

⟶ Partition function defines Sum over all Spinfoams !

Group Field Theories: a 2nd quantization of LQG

- Consider spin foams as dual to 4d triangulations

SF vertex $\leftrightarrow$ 4-simplex
SF edge $\leftrightarrow$ tetrahedron
SF face $\leftrightarrow$ triangle

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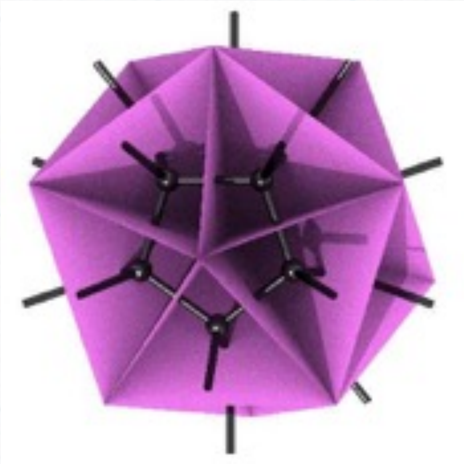

SF vertex ⟷ 4-simplex
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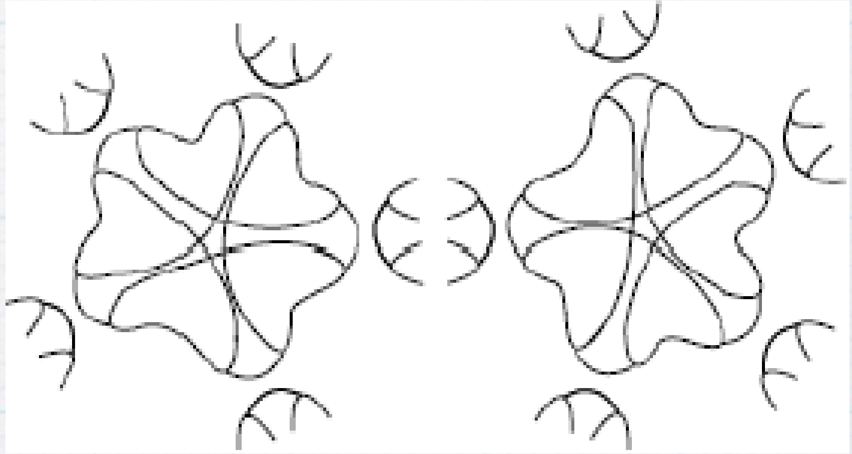

Group Field Theories: a 2nd quantization of LQG

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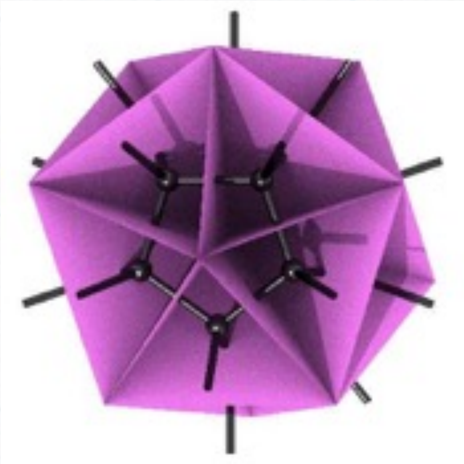
- Introduce field that represents quantum tetrahedron



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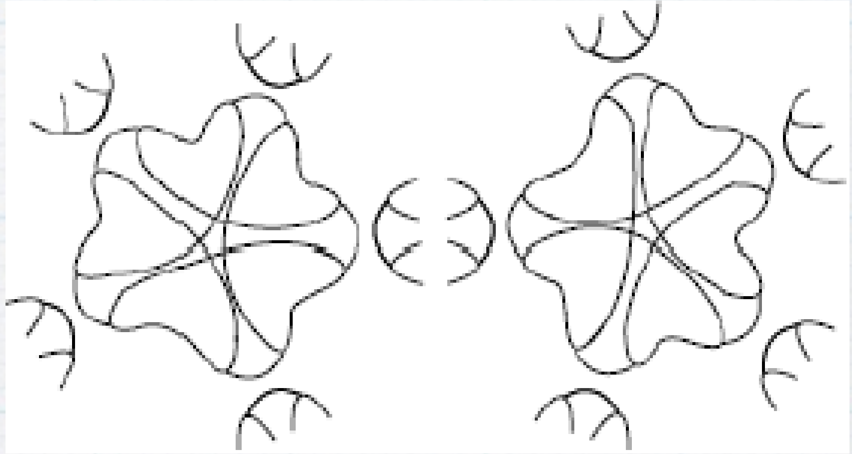

$$\phi(g_1, g_2, g_3, g_4) \in L^2(\mathrm{SU}(2)^{\times 4}/\mathrm{SU}(2))$$

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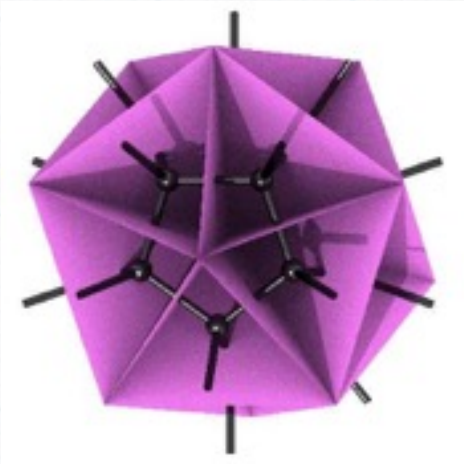

- Consider spin foams as dual to 4d triangulations
- Generate 4d triangulations as Feynman diagrams
- Introduce field that represents quantum tetrahedron
- Define « Group Field Theory » such that Feyn diag evaluations reproduce SF amplitudes

SF vertex $\longleftrightarrow$ 4-simplex
SF edge $\longleftrightarrow$ tetrahedron
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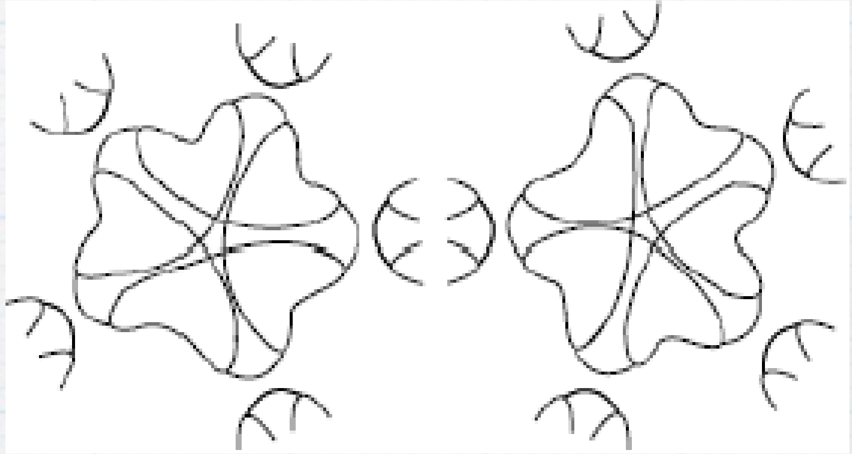

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a non-local Field Theory

$$S[\phi]=\frac{1}{2}\int[dg]|\phi|^2+\lambda\int[dg]\phi\phi\phi\phi\phi+\dots$$

Group Field Theories: Tensor Model Renormalization

Group Field Theory is the Non-Perturbative Definition of Spinfoams

But do they make sense non-perturbatively ??

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Recent Progress (breakthrough !) :

- Large N limit for tensor models — Gurau, Bonzom
- Controlling 4d topologies and taming sum through coloring/decoloring tensor models
- Renormalisable GFTs — Rivasseau, Carrozza
- Application to Condensed Matter :
  - Tensor Networks
  - SYK models

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We want a whole class of Spinfoam models, with a renormalization/coarse-graining flow

Group Field Theories: Tensor Model Renormalization

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Still a lot of work to do on spinfoams !

(Loop) Quantum Gravity

1. What is Quantum Gravity about?
2. Loop Quantum Gravity 1.0.1
3. Spinfoam Path Integrals
4. **Applications and Phenomenology**

- Loop Quantum Cosmology
- Quantum Black Holes
- Particle Physics: Non-Commutative Geometry

Quantum Cosmology for LQG

Loop Quantum Cosmology	GFT Cosmological Condensate
Ashtekar, ...	Oriti
• Classical symmetry reduction • Explicit & Predictive • Full Cosmology with inflation & inhomogeneities	• Gross-Pitaevski eqn from GFT perturbations • Gives effective Friedman eqn

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Modified Friedman eqn

$$H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$$

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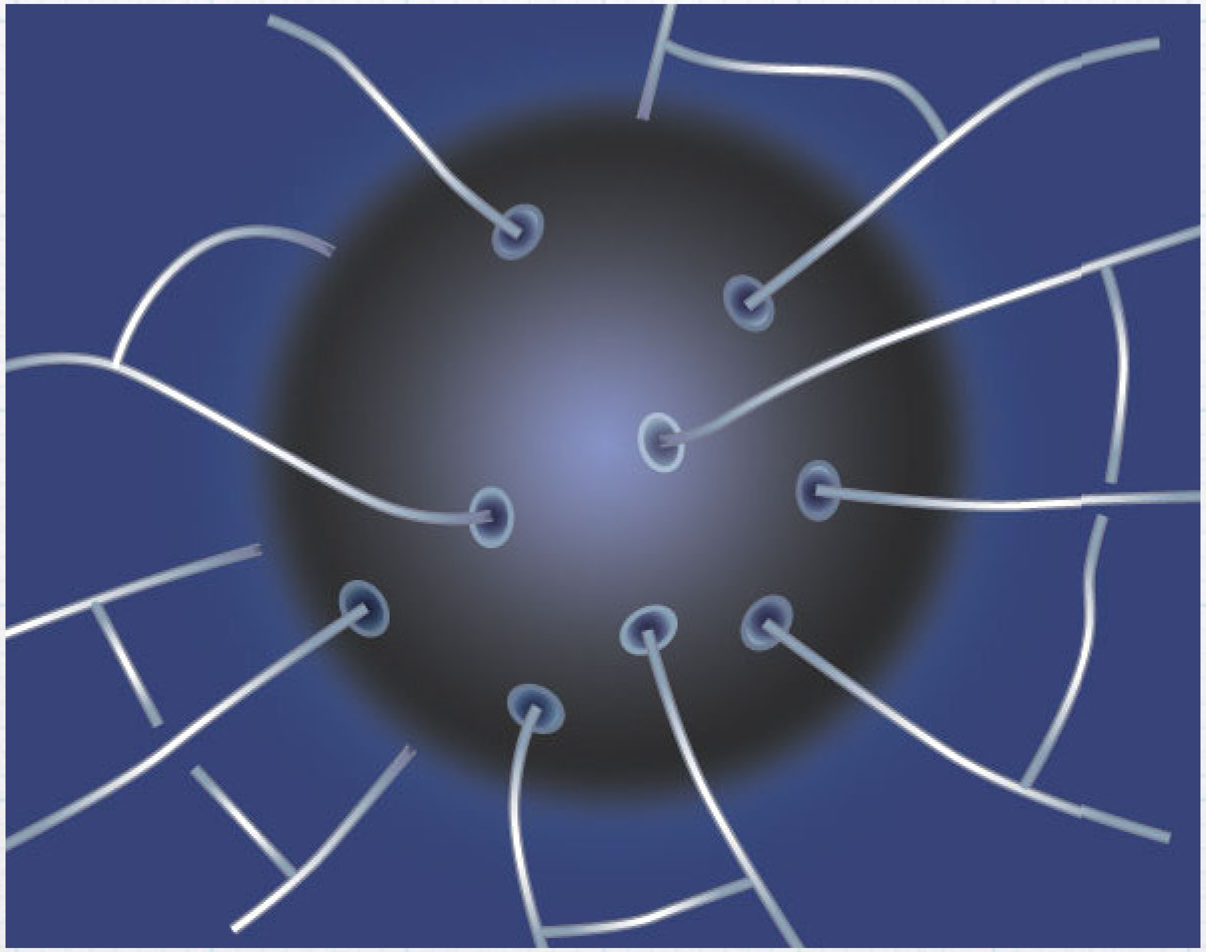
Regularized singularity with Big Bounce

Black Holes and Horizons in LQG



Perez, Noui, ...

Effective QFT for matter: NC Geometry

Integrating out Quantum Gravity effects :

$$e^{iS_{eff}[\phi]} = \int [dg]\, e^{iS_{grav}[g]+iS_{matter}[\phi,g]}$$

Program can be carried out explicitly for 3d QG : Freidel, L

- Particles as defects in Spinfoam
- Particle properties in terms of geometrical observables (LQG holonomy-flux)
- Interpret spinfoam amplitudes with particles as deformed Feynman diagrams for matter field
- Emergent non-commutative Geometry

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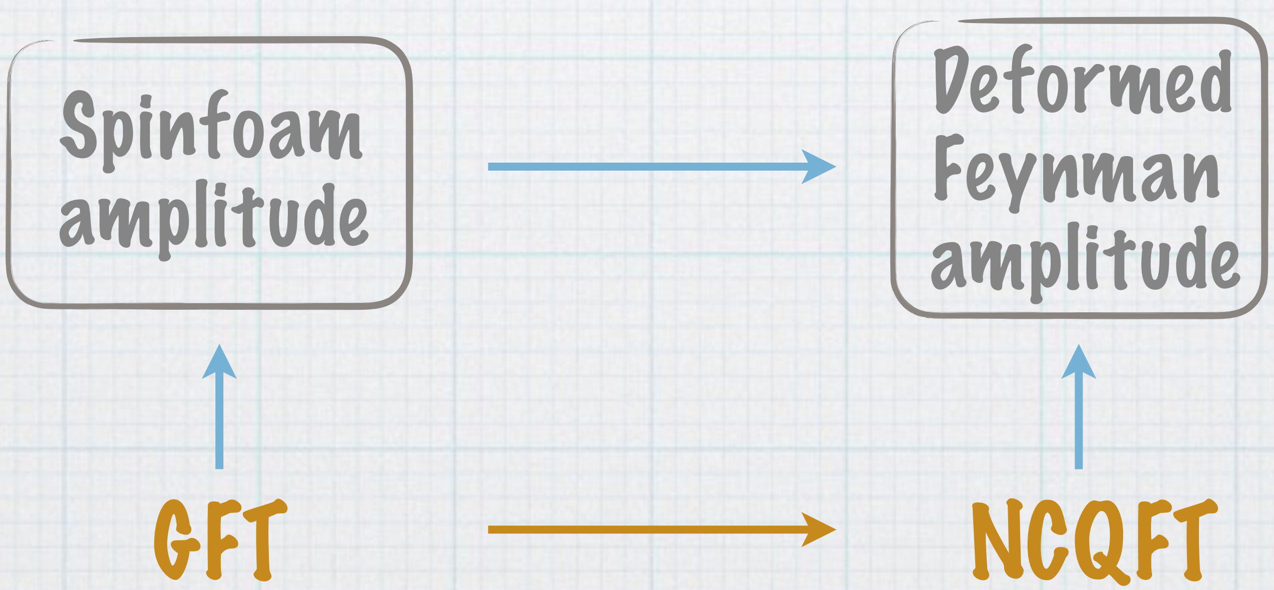
- Emergent non-commutative Geometry
- Can be seen directly at GFT level



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Similar Expectation for 4d spinfoam QG :

Effective deformed special relativity
with kappa-deformed Poincaré symmetry

Amelino-Camelia

c, m_{Planck}
Universal constants

→ Relative locality Freidel & al.

Reconstructing the Geometry (in Progress)

Towards explicit Holography in LQG

Geometry from Entanglement on Spin Network

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QG from QI ?

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Operational QFT pt of view:
bulk from boundary data ?

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Bulk-Boundary Dualities

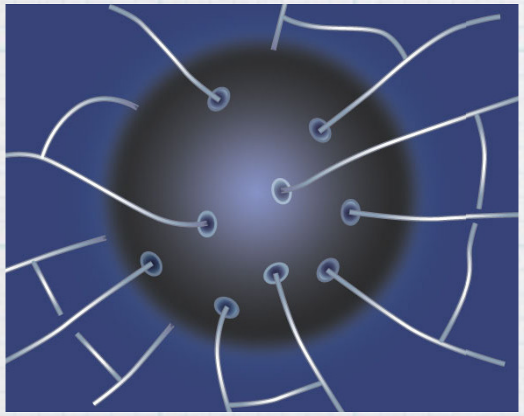
e.g. Duality between 3d Spinfoam QG & 2d Ising on boundary

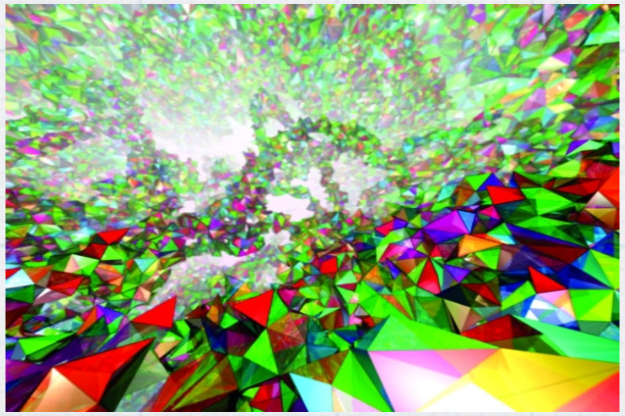
Bonzom, L

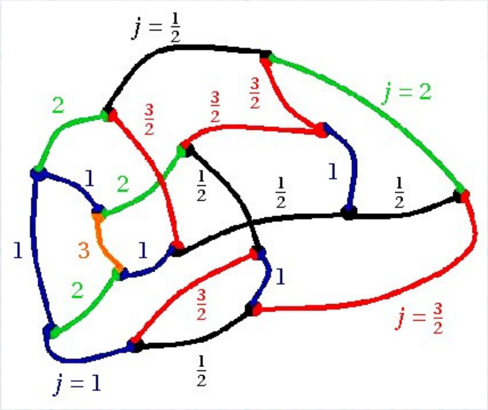
LQG as Evolving Network of Surfaces (Bubbles)

Freidel, Pranzetti

Thank you for your attention !





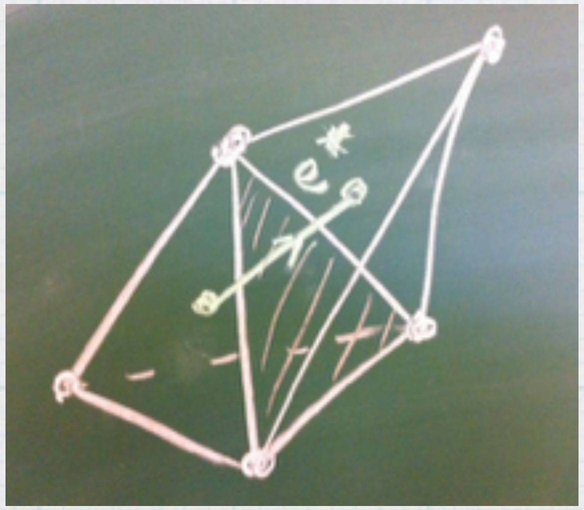


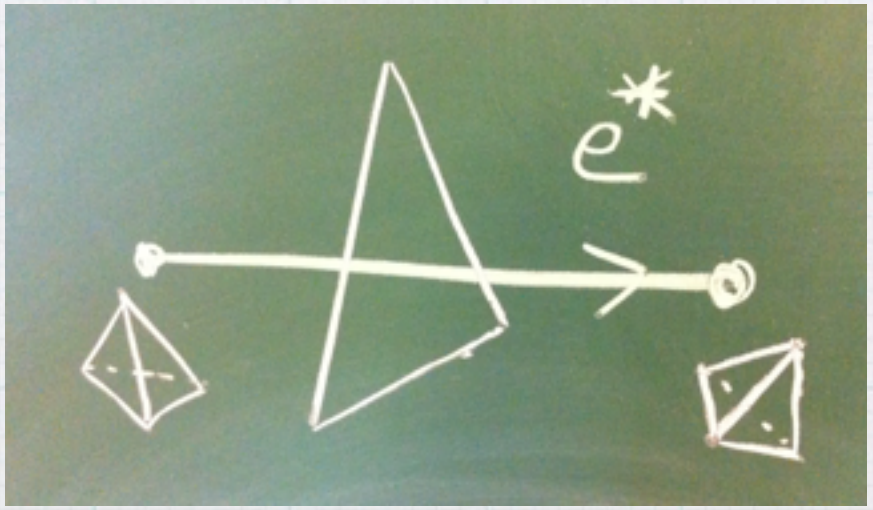
3d Quantum Gravity: Spinfoams & Spin Networks

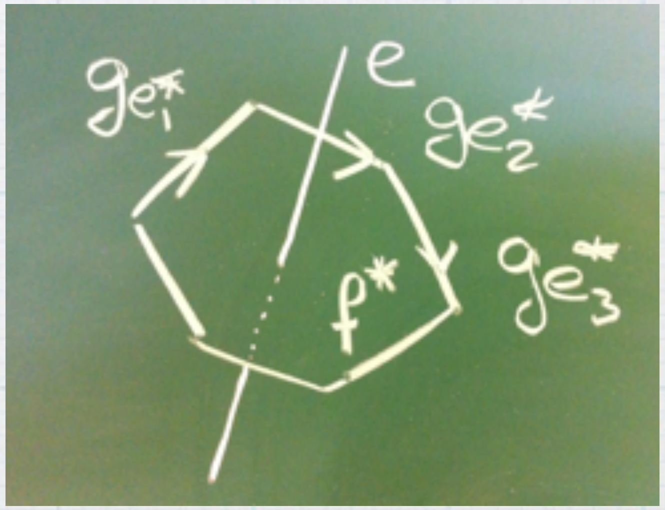
3d gravity as a TQFT can be exactly spinfoam quantized:

Topological field theory → Can be discretized exactly

1. Choose a 3d triangulation (cellular decomposition works too)
2. Define dual 2-complex, the **spinfoam**
3. Discretize connection along dual edges $g_{e^*} \in \mathrm{SU}(2)$
4. Discretize triad along edges $X_e \in \mathfrak{su}(2)$







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- Triad along edges $X_e \in \mathfrak{su}(2)$

X's are Lagrange multipliers imposing flatness of connection around dual faces (i.e around edges)

$$G_e = G_{f^*} = \overrightarrow{\prod_{e^* \in \partial f^*}} g_{e^*}$$

$$Z = \int \mathrm{d}e \mathrm{d}A\, e^{iS[e,A]} = \int \mathrm{d}A\, \delta(F[A]) = \int \prod_{e^*} \mathrm{d}g_{e^*} \prod_e \delta(G_e)$$

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We decompose onto irreps of SU(2) i.e **spins** :

$$Z = \int \prod_{e^*} \mathrm{d}g_{e^*} \sum_{\{j_e \in \frac{\mathbb{N}}{2}\}} \prod_e (2j_e+1)\chi_{j_e}(G_e)$$

and we integrate over all group elements,

leaving us with spin recoupling symbols

3d Quantum Gravity: Spinfoams & Spin Networks

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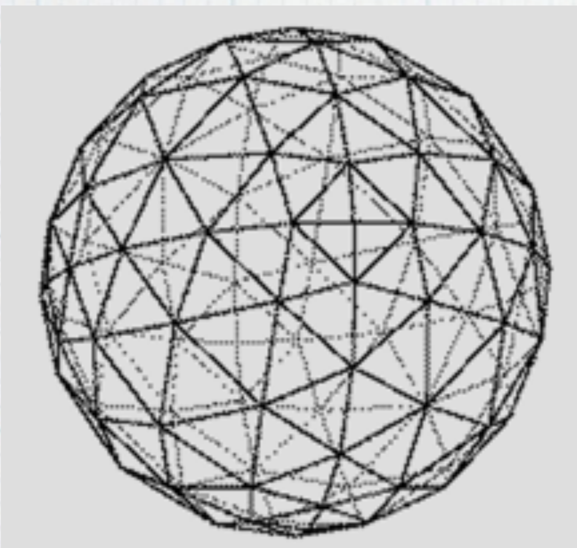

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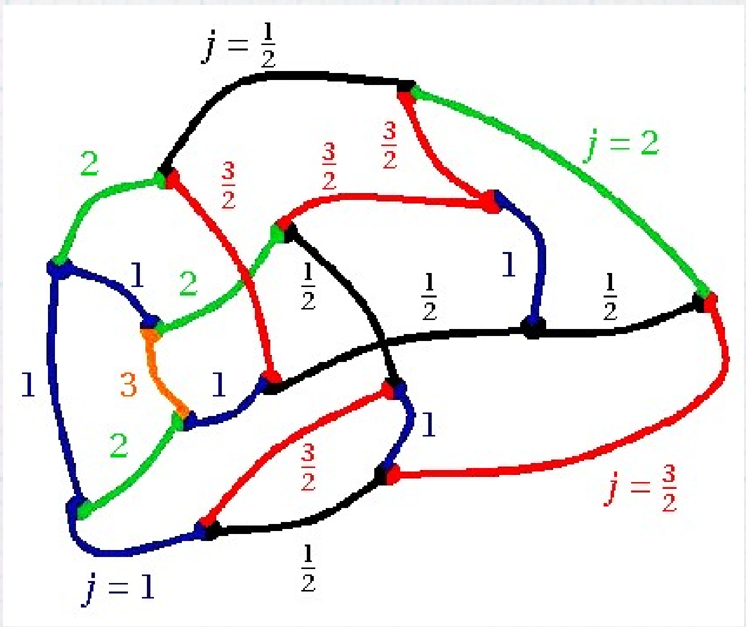
- Amplitude as product of 6j-symbols

$$\mathcal{A}_\Delta = \sum_{\{j_e\}} \prod_e (2j_e + 1) \prod_T \{6j\}$$

- Boundary 2d triangulated surface or dual 3-valent graph
- Spins on boundary edges or dual links: **boundary spin network**



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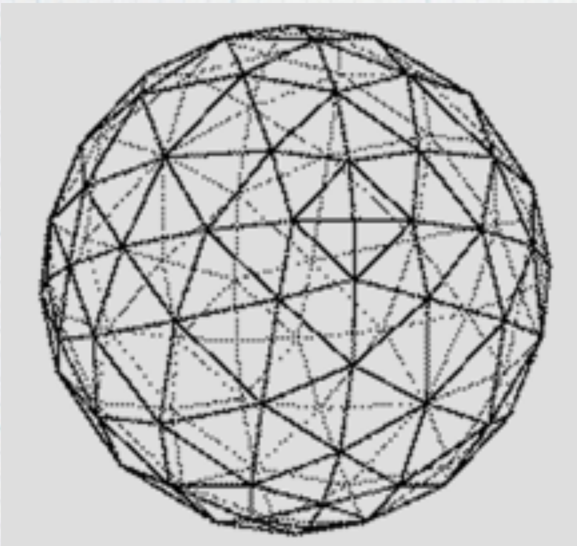

- Assume trivial spherical topology
- Use topological invariance to gauge fix bulk
- PR amplitude becomes projector on flat connection

$$\mathcal{A}_\Delta = \mathcal{A}_{\partial\Delta} = \langle \mathbb{1} | \psi \rangle = \psi(\mathbb{1})$$

For a trivial topology, amplitude expressed explicitly in terms of boundary data:

evaluation of boundary spin network