Coarse-Graining Loop Quantum Gravity

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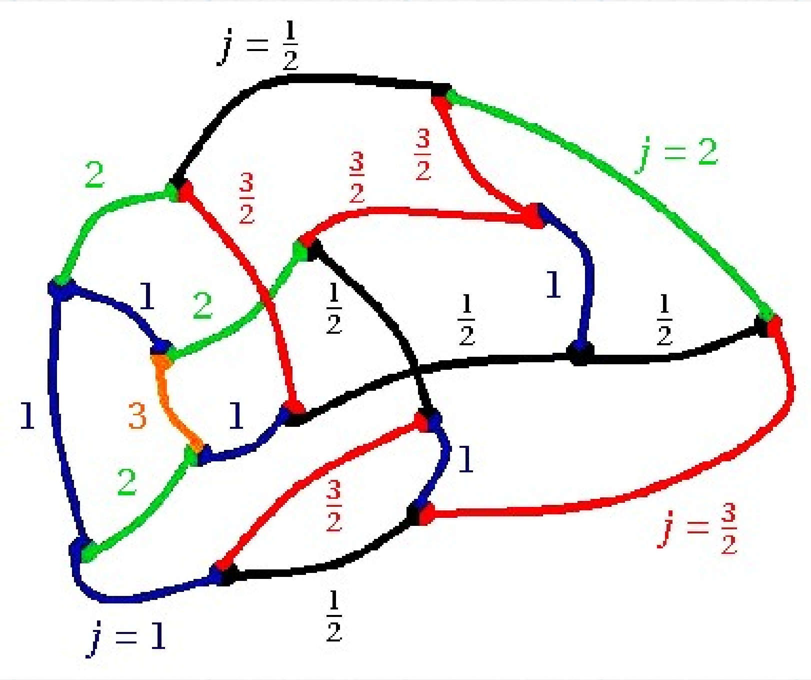
Loops' 17 Conference

arXiv 1603.01117 & 1704.04067 & more

Coarse-Graining Spin Networks

- Why coarse-grain spin network ?
- How to coarse-grain spin networks?

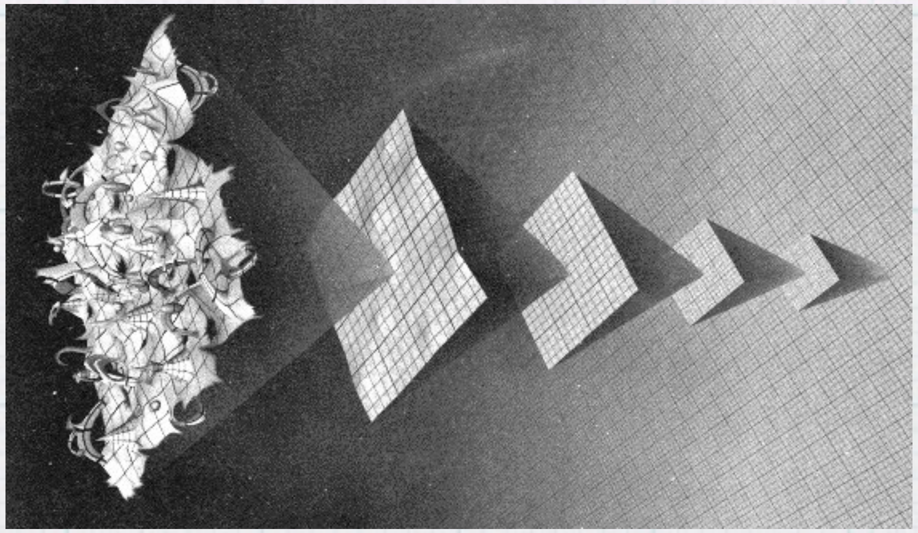


Why Coarse-Grain Spin Networks ?

The Basic Motivation :

Spin networks = interpreted as Discrete Geometries at Planck scale

Need to coarse-grain to probe geometry at all scales
and understand continuum limit towards smooth manifolds



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Goal : Build renormalization group flow for geometry states

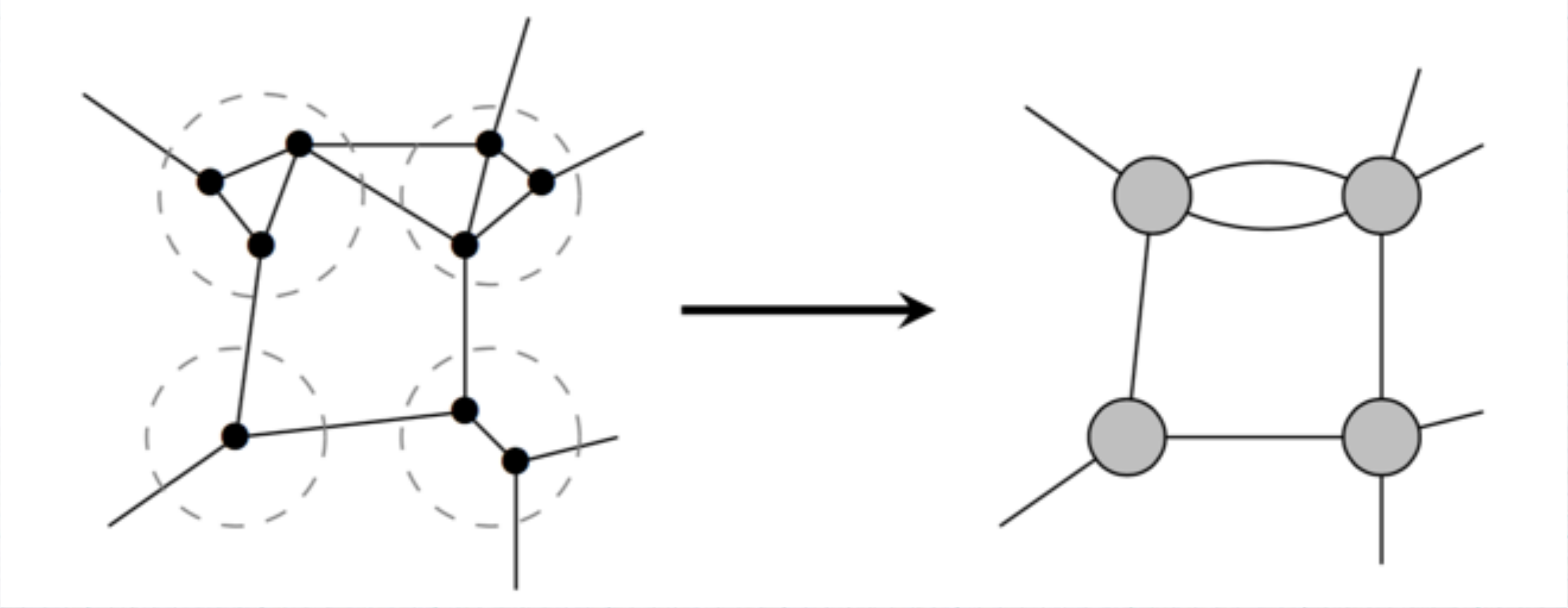
↪ Necessary to extract systematic (L)QG corrections to GR

↪ Necessary to study phase diagrams and phase transitions

The Basic Setting: coarse-graining the network

Spin networks defined on a graph :

fundamental graph ⟶ effective graph



- we partition network into bounded regions
- we coarse-grain each region into an effective vertex

The Basic Setting: coarse-graining the network

3 Big Questions :

- What are the relevant d.o.f. of geometry to keep ?
- How to choose the effective graph ?
- What data is attached to the effective nodes and links ?

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Are we erasing physical bulk d.o.f.s or gauge d.o.f.s ??

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Property of quantum state or property of observer ??

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Property of quantum state or property of observer ??

Pt of view : Requires a measure of « classicality » of geometry

The Basic Setting: coarse-graining the network

3 Big Questions :

- What are the relevant d.o.f. of geometry to keep ?
- How to choose the effective graph ?
- What data is attached to the effective nodes and links ?

→ Property of quantum state or property of observer ??

Pt of view : Choice of effective graph = choice of observer

↓

Proposal: project graph-changing dyn on fixed background lattice

Choice of effective graph = choice of observer

- Network as lattice of observation at finite resolution
- Defines a cut-off between microscopic/macroscopic
- Gauge-fixing of diffeomorphisms

↓

Proposal: project graph-changing dyn on fixed background lattice

The Basic Setting: coarse-graining the network

3 Big Questions :

- What are the relevant d.o.f. of geometry to keep ?
- How to choose the effective graph ?
- **What data is attached to the effective nodes and links ?**

↪ Spin networks are not enough !

... spin networks are patchworks of flat regions

Dressed Spin Networks

Introducing New Structures for Quantum States in LQG !!

Dressed Spin Networks

Introducing New Structures for Quantum States in LQG !!

Dressed spin networks with extra data at each node & link
to encode local curvature & torsion

• Loopy & tagged spin networks	Charles, L	1603.01117
• Double spin networks	Charles, L	1607.08359
• q-deformed spin networks	BDGL & HXKR	1402.2323 1509.00458
• « Drinfeld tube » networks	the B-team	1412.3752 1607.08881
• Loop gravity string	the LAD's	1611.03668

That's for the basic motivation ...

The Deeper Motivation: towards Holography

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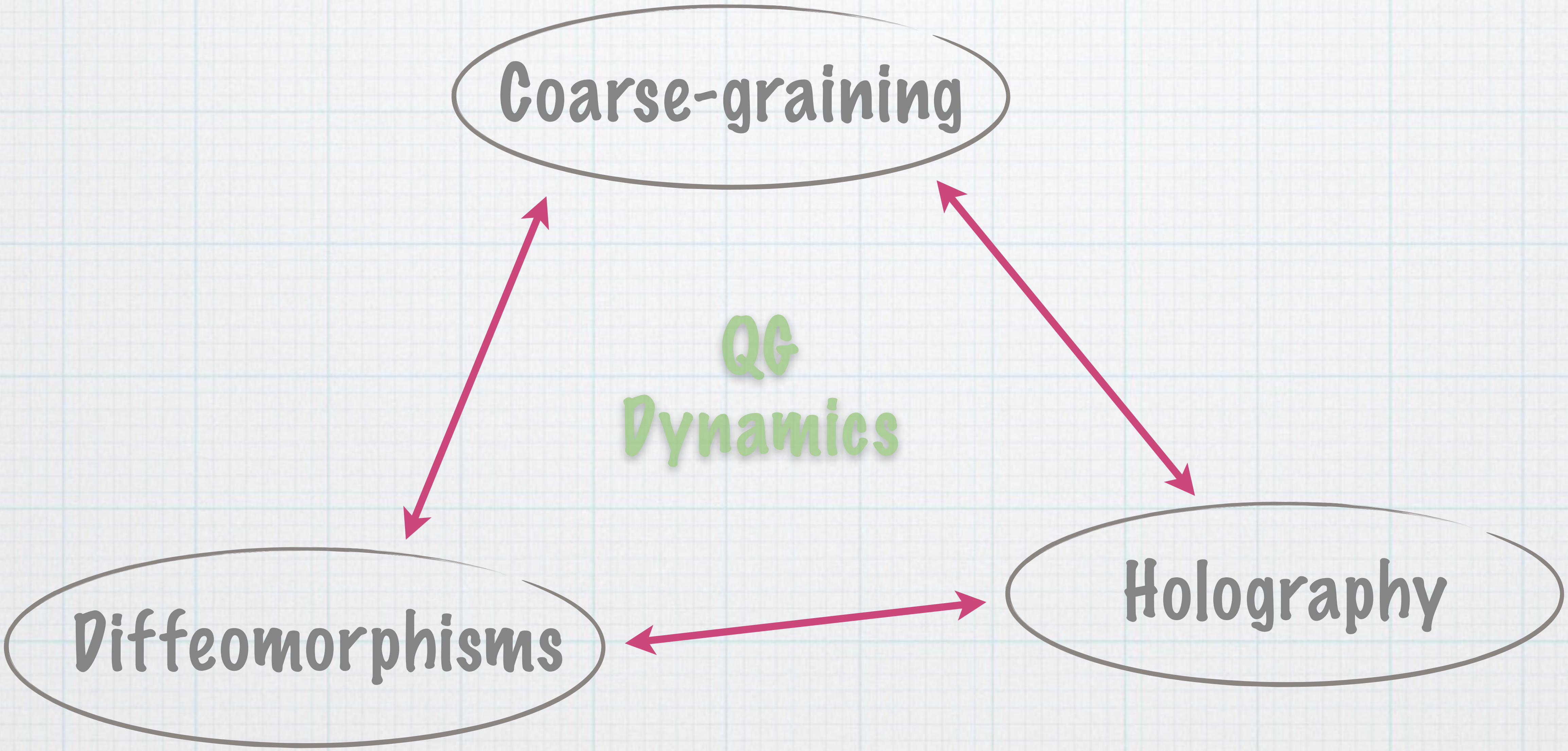
A tryptic of related issues:



The Deeper Motivation: towards Holography

A tryptic of related issues:

Renormalisation flow,
Notion of scale,
Phase transitions, ...

Coarse-graining

QG
Dynamics

Diffeomorphisms

Holography

Hamiltonian constraints,
Notion of observer, Evolution, ...

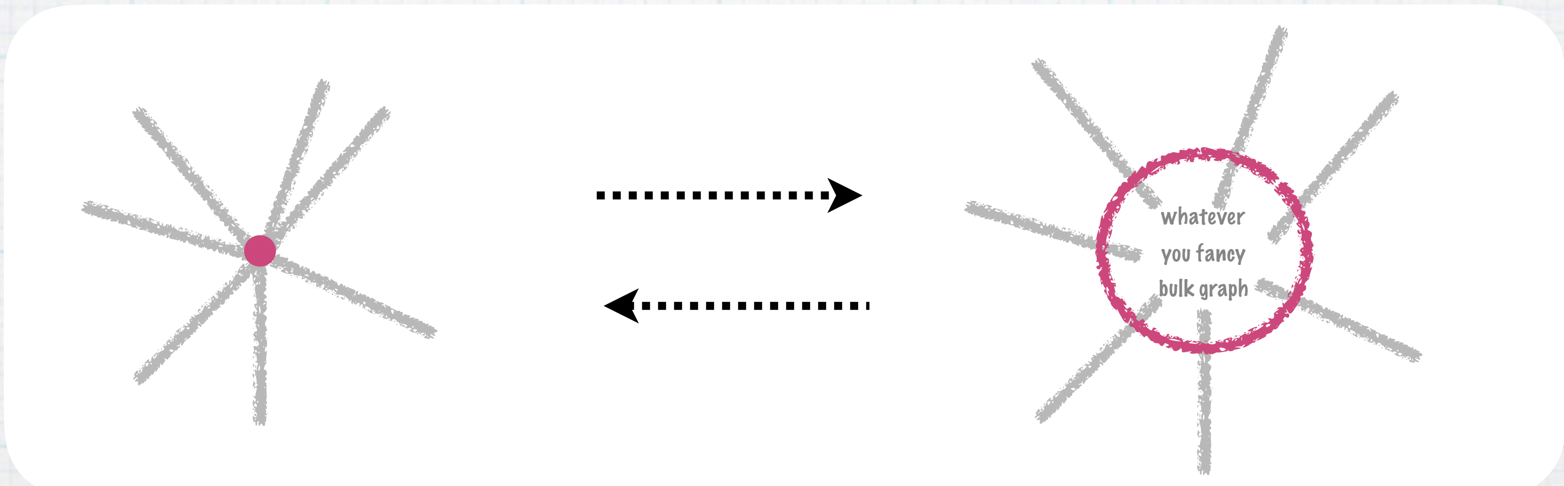
Gauge-gravity duality,
AdS/CFT, bulk-boundary, ...

The Deeper Motivation: towards Holography

Coarse-graining ⟷ **Holography**

Kinematical level — Dynamical level

A common setting in LQG : it's all about surfaces



Intertwiner at node interpreted as dual surface

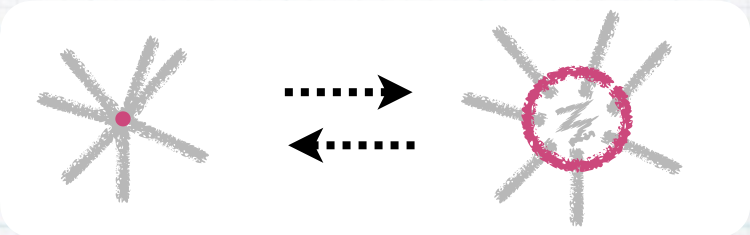
Bounded region geometry made of several nodes projected to boundary state on surface

The Deeper Motivation: towards Holography

Coarse-graining ⟷ **Holography**

Kinematical level — Dynamical level

The same questions :



- How much geometry are we losing by projecting on boundary surface ?
- How much bulk can we reconstruct from the boundary state ?

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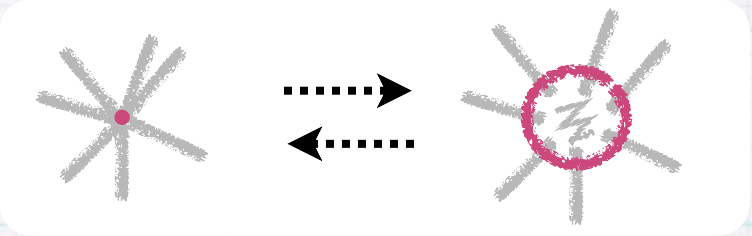

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Interlaced with understanding diffeo's in LQG :

Hamiltonian constraint operators ⟷ Equivalence relation between spin networks defined on a priori different graphs

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Coarse-graining ⟷ **Holography**

Kinematical level | Dynamical level

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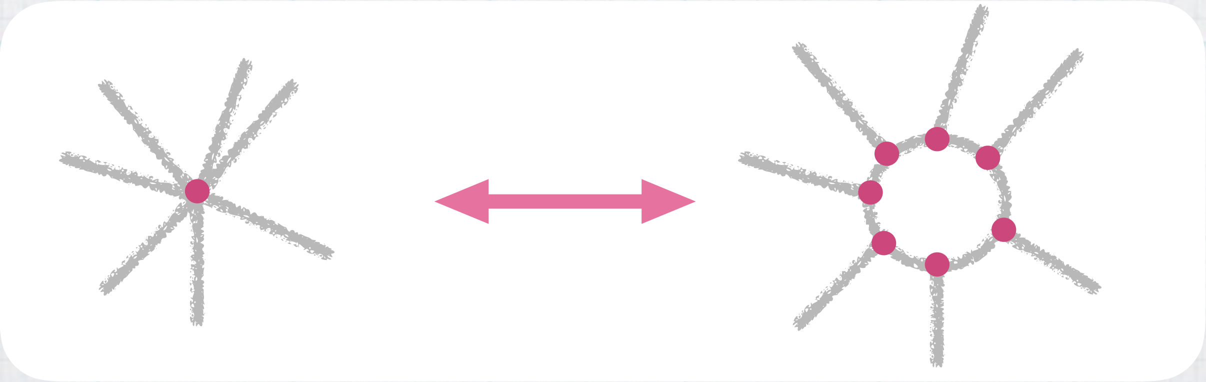
Part of bulk data is physical, part is gauge: how to distinguish them ?

e.g. BF theory



bulk loops are gauge

The Deeper Motivation: towards Holography

Coarse-graining ⟷ **Holography**

Kinematical level — Dynamical level

Interlaced with understanding diffeo's in LQG :

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Part of bulk data is physical, part is gauge: how to distinguish them ?

and for gravity ?

The Deeper Motivation: towards Holography

Coarse-graining $\longleftrightarrow$ **Holography**

Kinematical level — Dynamical level

Interlaced with understanding diffeo's in LQG :

Hamiltonian constraint operators $\longleftrightarrow$ Equivalence relation between spin networks defined on a priori different graphs

Part of bulk data is physical, part is gauge: how to distinguish them ?

Consider yet-to-be-defined coarse-graining procedure, with no actual loss of info, such that boundary states allow faithful rep of relevant physical bulk obs ...

$\longrightarrow$ **This would be holography in LQG**

How to Coarse-Grain Spin Networks ?

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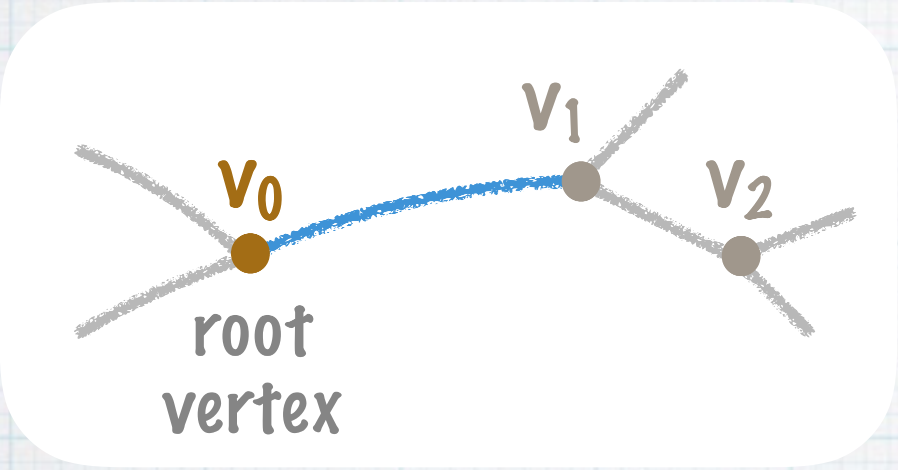
An essential(ly) simple procedure:

« Coarse-graining by Gauge-fixing »

Allows to reduce any bounded region of a spin network to a single vertex

Gauge-Fixing and Frame Synchronization

Let's choose a root vertex and start with one link



Use gauge-invariance at vertex v_1

$$\varphi(g_{v_0v_1}, g_{v_1v_2}, ..)$$
$$= \varphi(g_{v_0v_1}h_{v_1}^{-1}, h_{v_1}g_{v_1v_2}, ..)$$

Set parameter $h_{v_1} = g_{v_0v_1}$ to gauge-fix to $\tilde{g}_{v_0v_1} = g_{v_0v_1}h_{v_1}^{-1} = \mathbb{I}$

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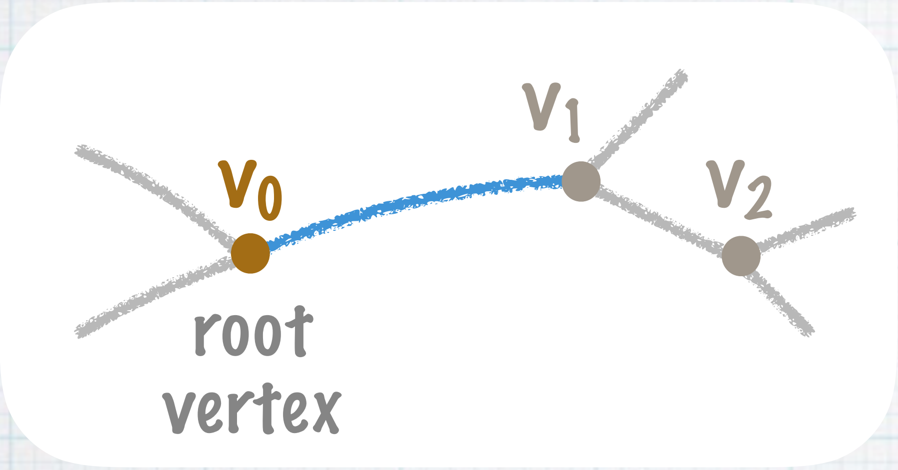

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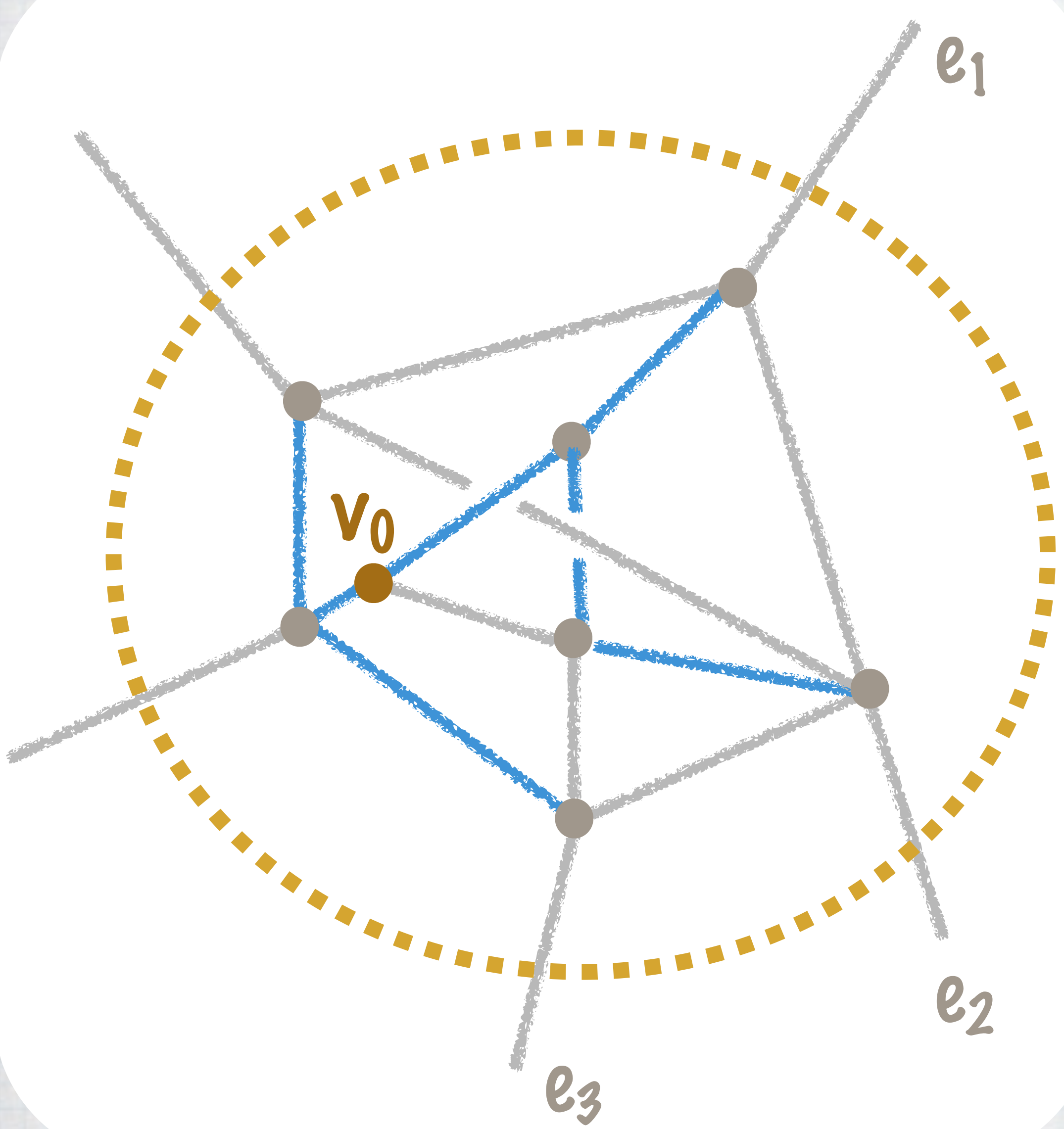
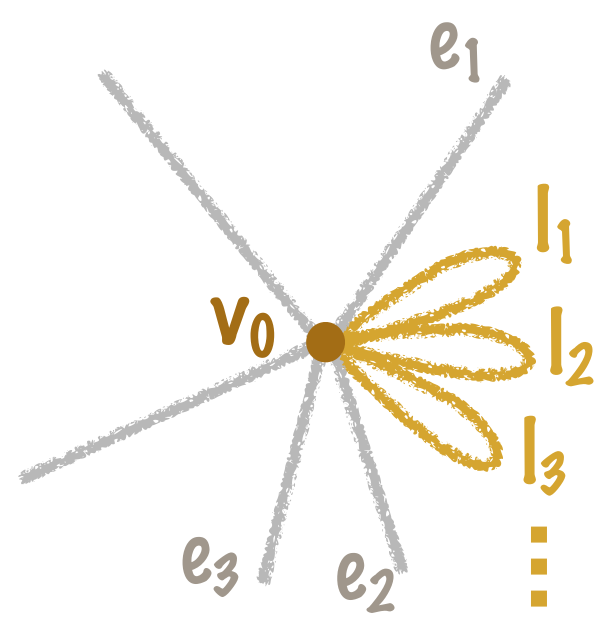
- Can develop gauge-fixing along tree in graph
- Set all holonomies on edges in tree to Identity
- Only remaining gauge invariance at root vertex v_0
- i.e. Synchronize the SU(2) frames along tree !

Gauge-Fixing to Loopy Vertices

So let's consider a bounded region and gauge-fix the holonomies on a max tree T on the bulk graph

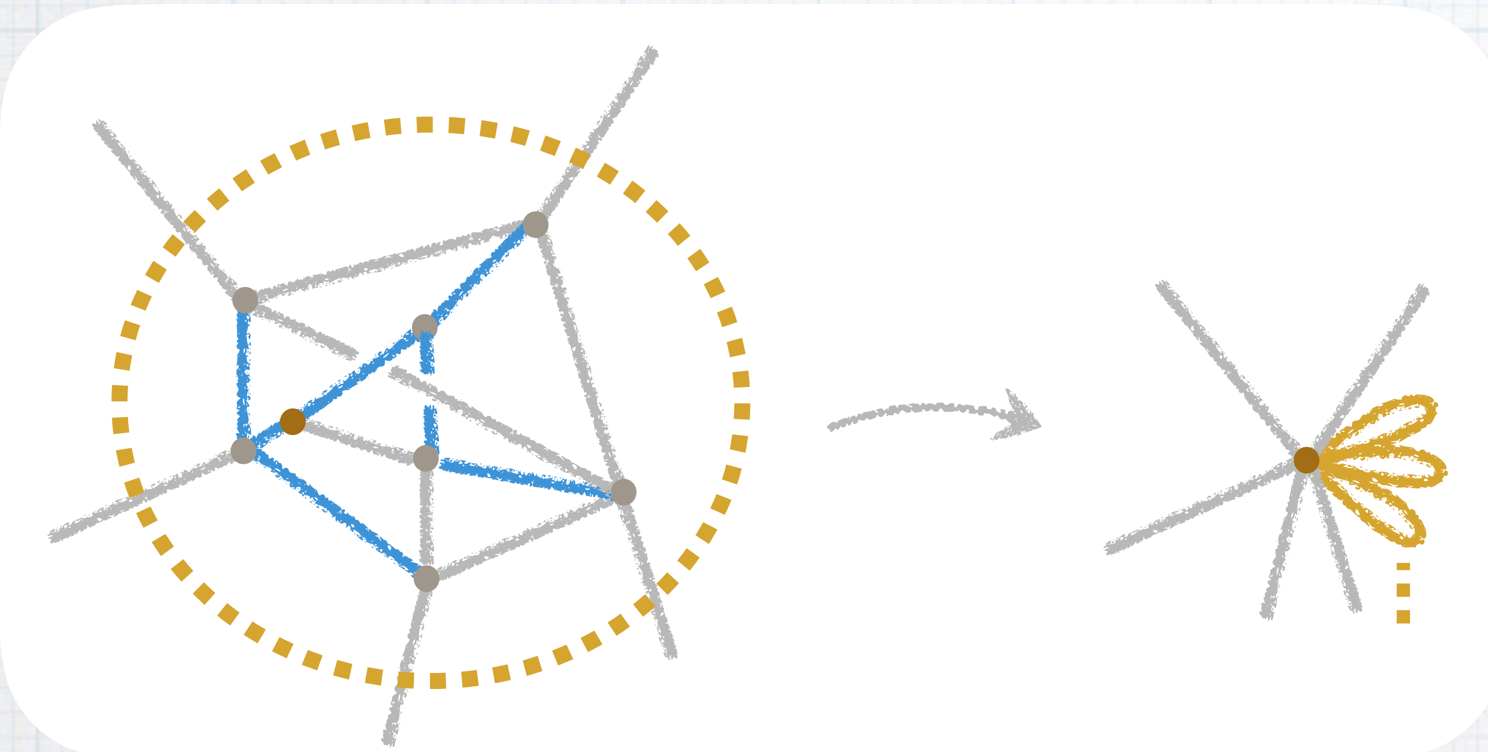


- Reduce bulk graph to root vertex
- One loop for each edge not in tree



little loops = local curvature excitations

Gauge-Fixing to Loopy Vertices

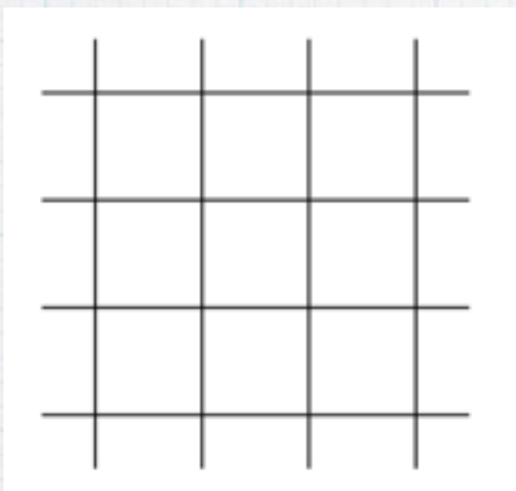


Are we losing any information by gauge-fixing ?

The Loopy Spin Network Proposal

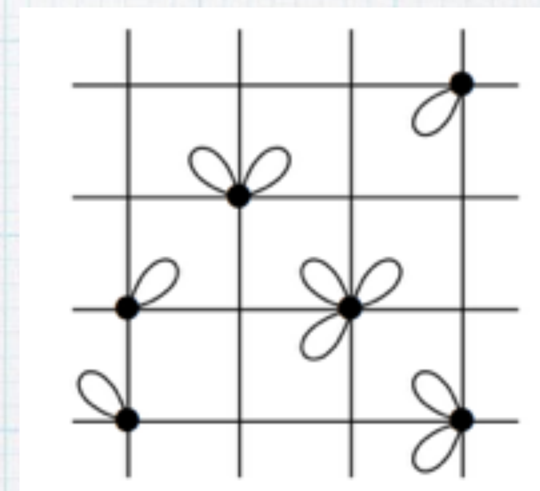
We can re-introduce a background lattice :

(L)QG on a fixed graph



improved

LQG on an effective background lattice



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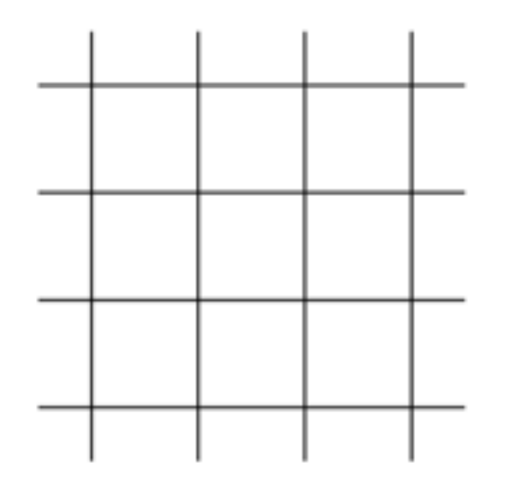

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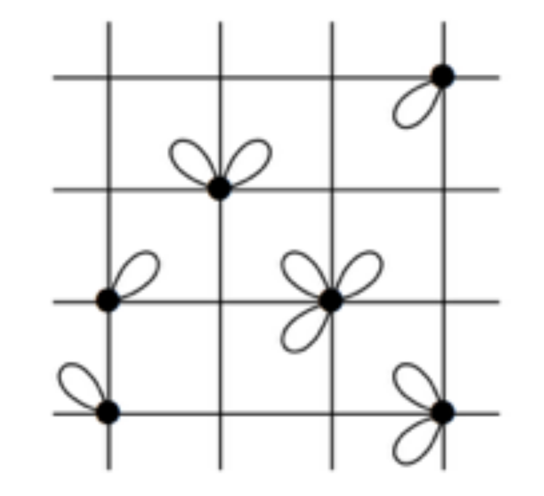


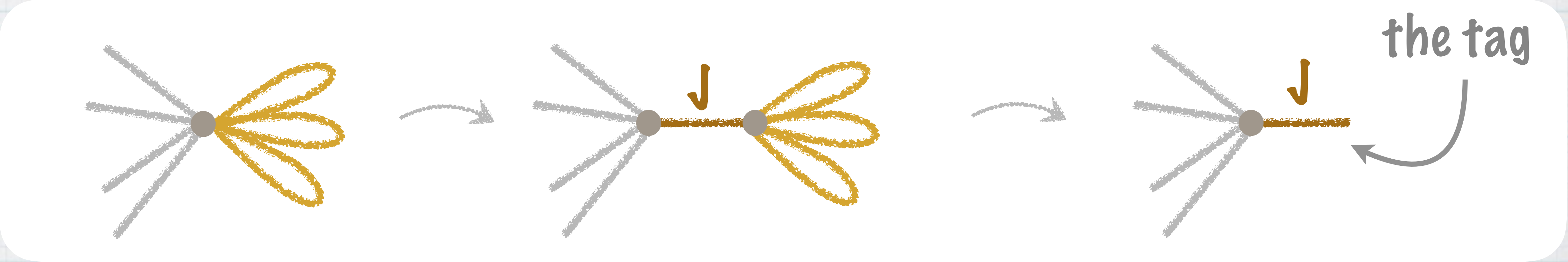
- Fock space of little loops at each vertex, as local d.o.f.s
- little loops account for fluctuations of bulk graph within each node

Possible to do effective graph-changing dynamics on a fixed lattice

From little loops to tags: the Closure Defect

What's the effects of the little loops ?

They create a non-trivial closure defect at each node ...



... so we coarse-grain more and define **tagged spin network**

tag = bulk curvature

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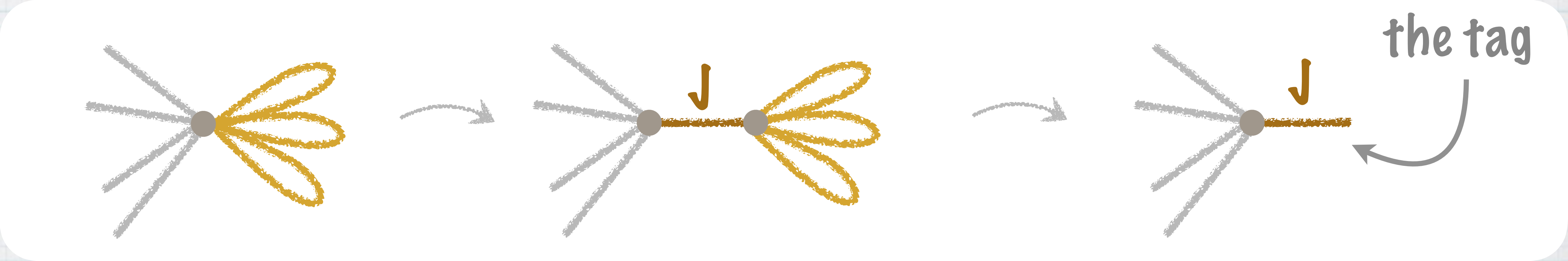


... so we coarse-grain more and define **tagged spin network**

tag = bulk curvature = energy ?

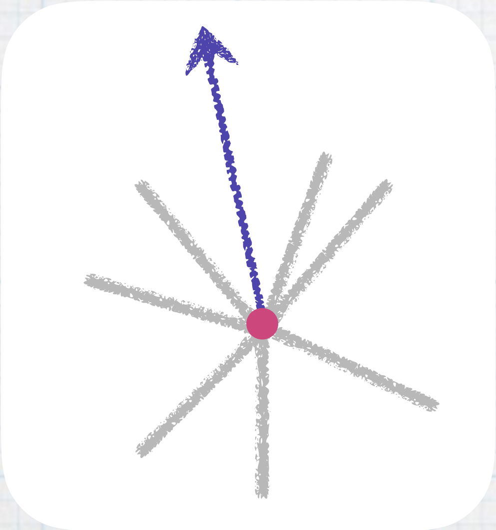
like having non-zero surface charge while imposing Gauss law as in 1611.08394

Perez, Cattaneo

From curvature excitations to Boosted Spin Networks

What should we do with a closure defect ?

We can always boost it back to the closure constraint !



$$\sum_{e \ni v} X_e \neq 0 \quad \xrightarrow[\text{boost}]{\Lambda} \quad \sum_{e \ni v} \tilde{X}_e = 0$$

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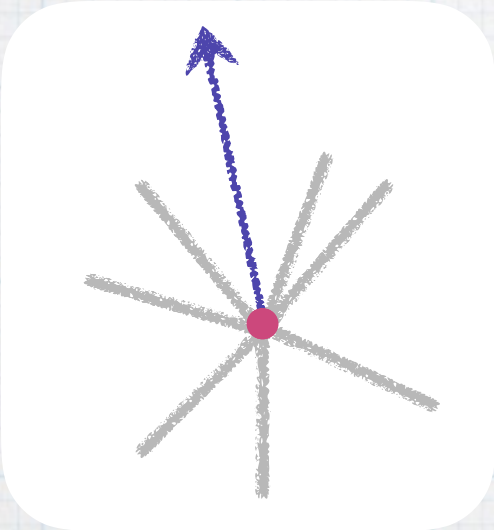

$$\sum_{e \ni v} X_e \neq 0 \quad \xrightarrow[\text{boost}]{\Lambda} \quad \sum_{e \ni v} \tilde{X}_e = 0$$

In terms of spinors : $X^a = \langle z|\sigma^a|z\rangle \in \mathbb{R}^3$

$$\sum |z_e\rangle\langle z_e| \not\propto \mathbb{I} \quad \xrightarrow[\text{boost}]{\Lambda} \quad \sum |\tilde{z}_e\rangle\langle \tilde{z}_e| = \Lambda \sum |z_e\rangle\langle z_e| \Lambda^{-1} \propto \mathbb{I}$$

From curvature excitations to Boosted Spin Networks

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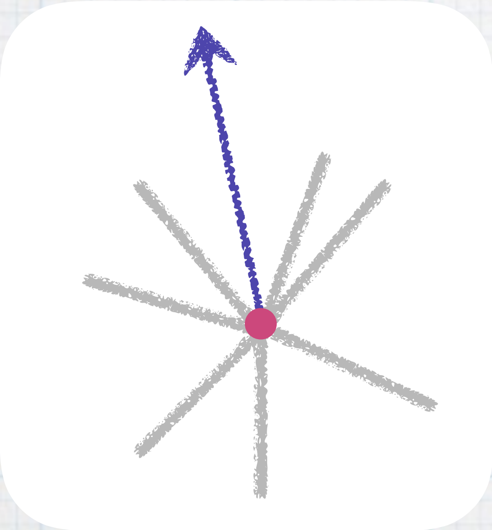

$$\sum_{e\ni v} X_e \neq 0 \xrightarrow[\text{boost}]{\Lambda} \sum_{e\ni v} \tilde{X}_e = 0$$

In terms of null-vectors : $\mathbf{X}^\mu = (|X|, X^a) = \langle z|\sigma^\mu|z\rangle \in \mathbb{R}^{1,3}$

$$\sum \mathbf{X}_e \ \text{timelike} \xrightarrow[\text{boost}]{\Lambda} \sum \widetilde{\mathbf{X}}_e = (\mathcal{A}, 0)$$

Rest area : $\mathcal{A} = \Big|\sum_e \mathbf{X}_e\Big|^2$ **is Lorentz-invariant**

From curvature excitations to Boosted Spin Networks

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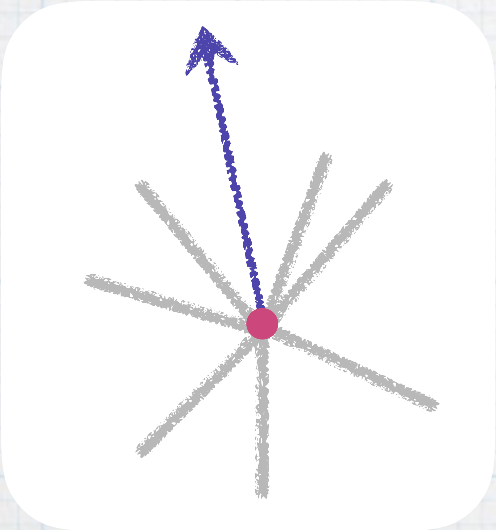
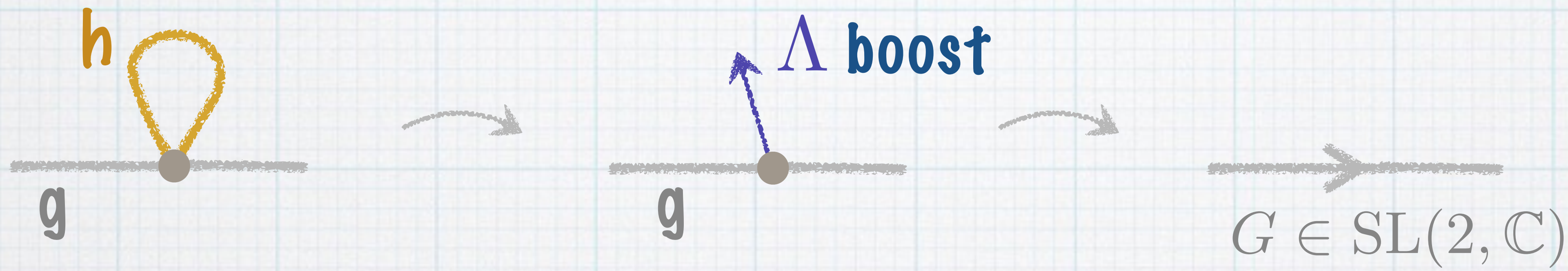


$$\sum_{e \ni v} X_e \neq 0 \quad \xrightarrow[\textbf{boost}]{\Lambda} \quad \sum_{e \ni v} \tilde{X}_e = 0$$

- Can change the space-time embedding to compensate for the tag
- Trade intrinsic curvature for extrinsic curvature
- Essential feature of Ashtekar-Barbero connection
- Coarse-graining affects 3d geometry but also 4d embedding

Little loops on the links : the Area « Propagator »

We apply the same logic to the spin network links :



Non-trivial mapping of dressed link with loop to SL(2,C) holonomy !

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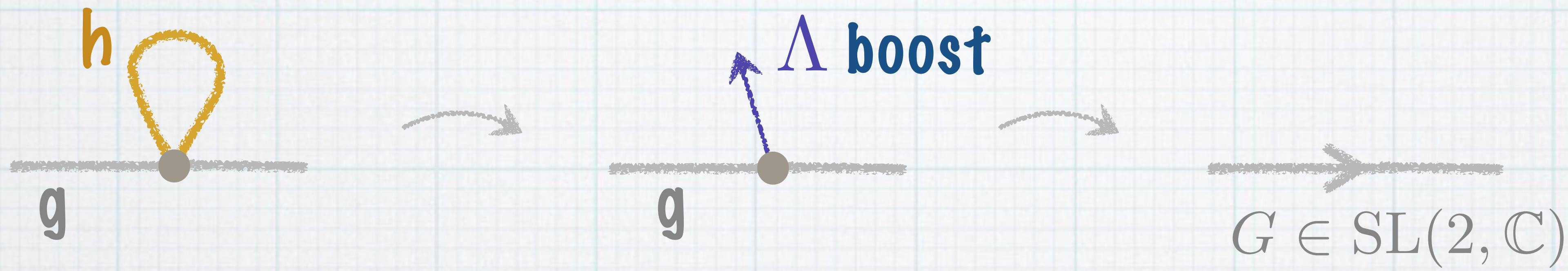

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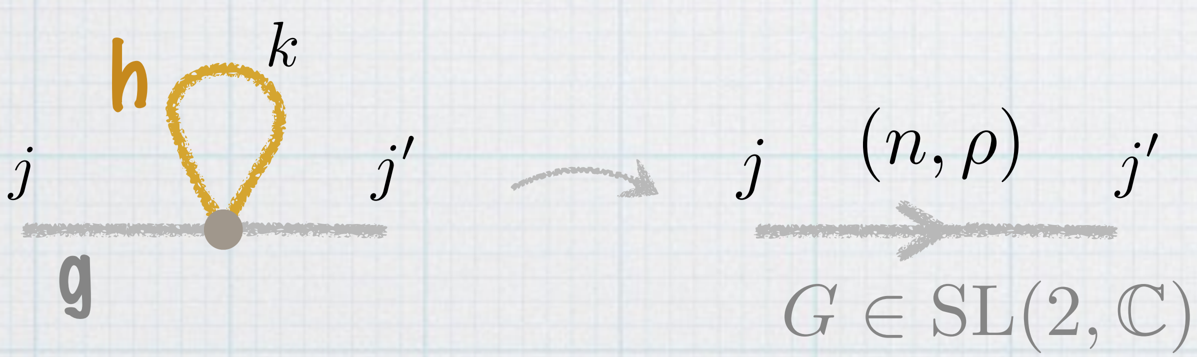
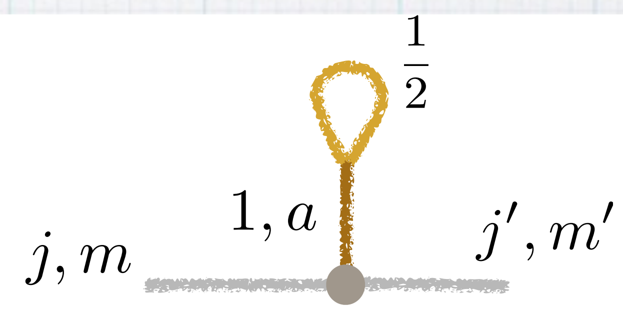
At the quantum level :





$$\chi(h\sigma^a)\langle j', m'|(j,m)\otimes(1,a)\rangle$$
$$=$$
$$A_{(n,\rho)}\langle (n,\rho)j', m'|\vec{u}\cdot\vec{K}|(n,\rho)j,m\rangle$$

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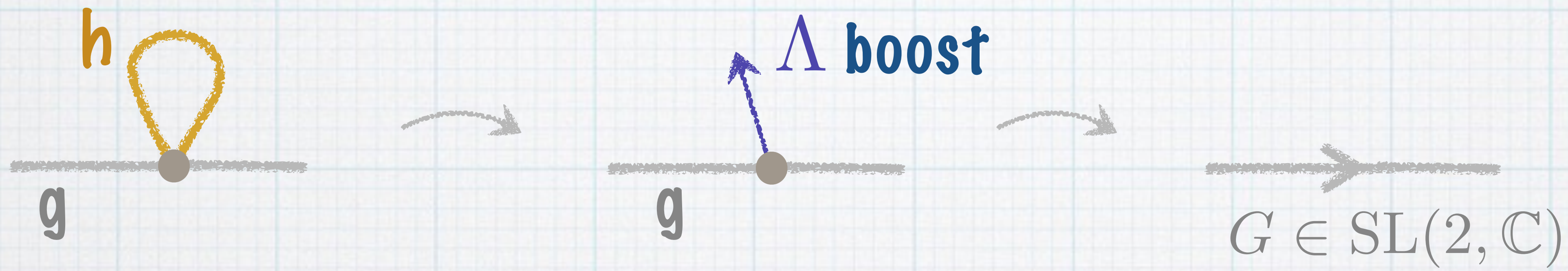

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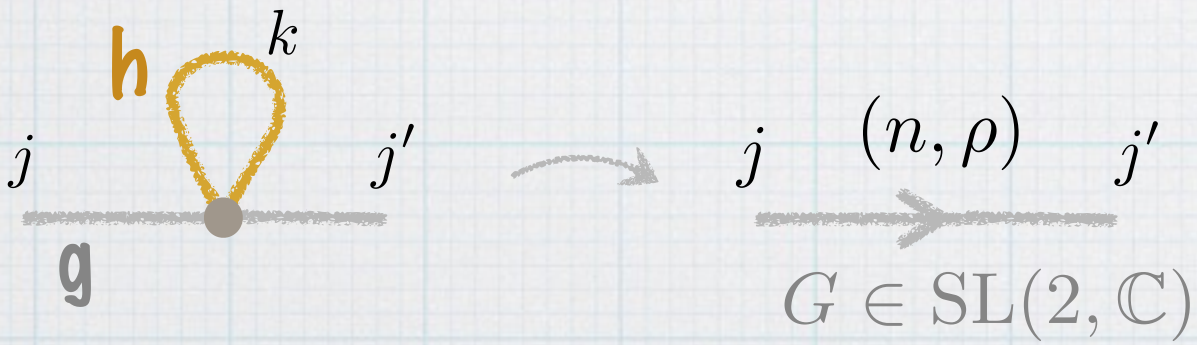

- Transition between spins on link
- Dressed link with curvature/boost
- Similar to spinfoam formalism

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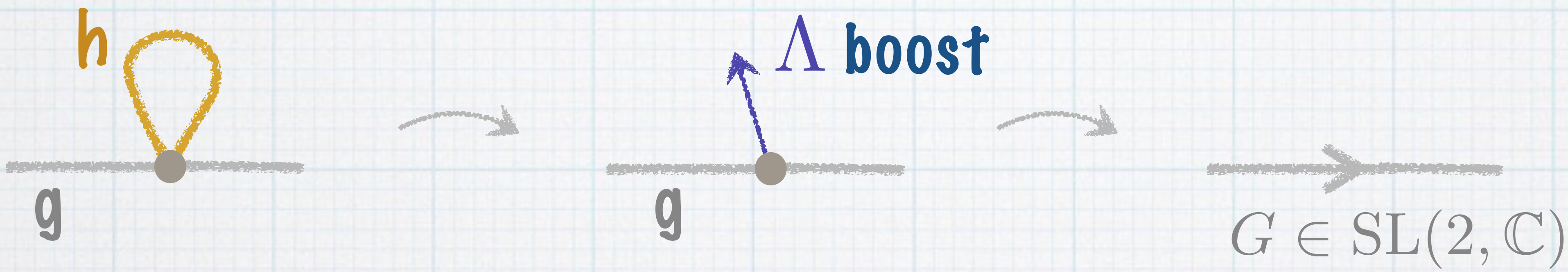

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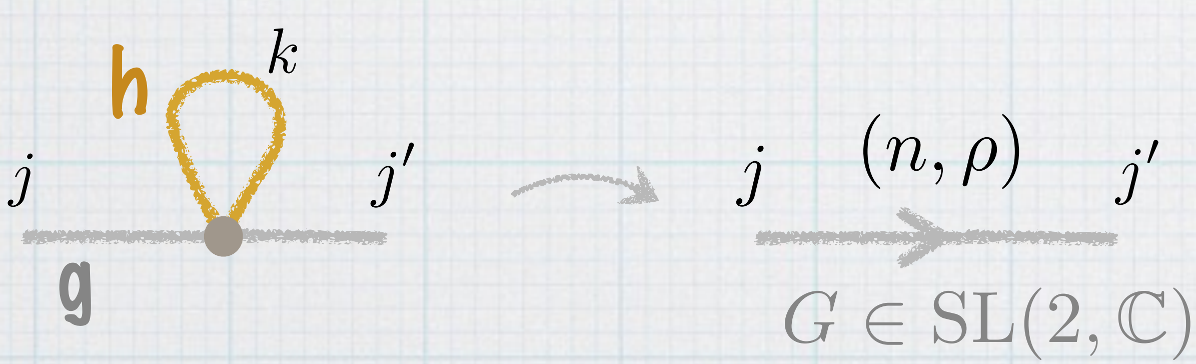

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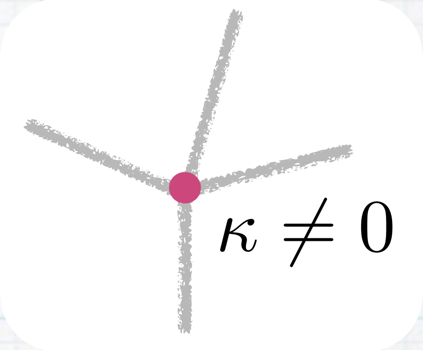
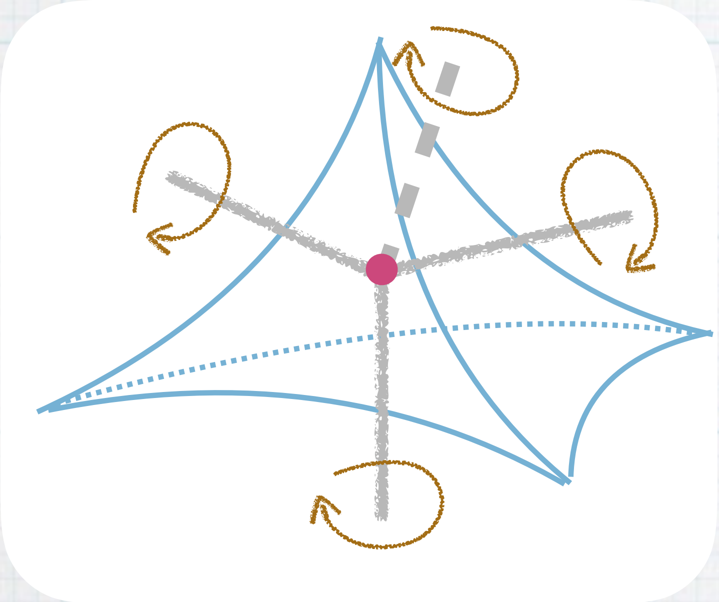
Area waves along links ?

And the story goes on..

dressed spin networks

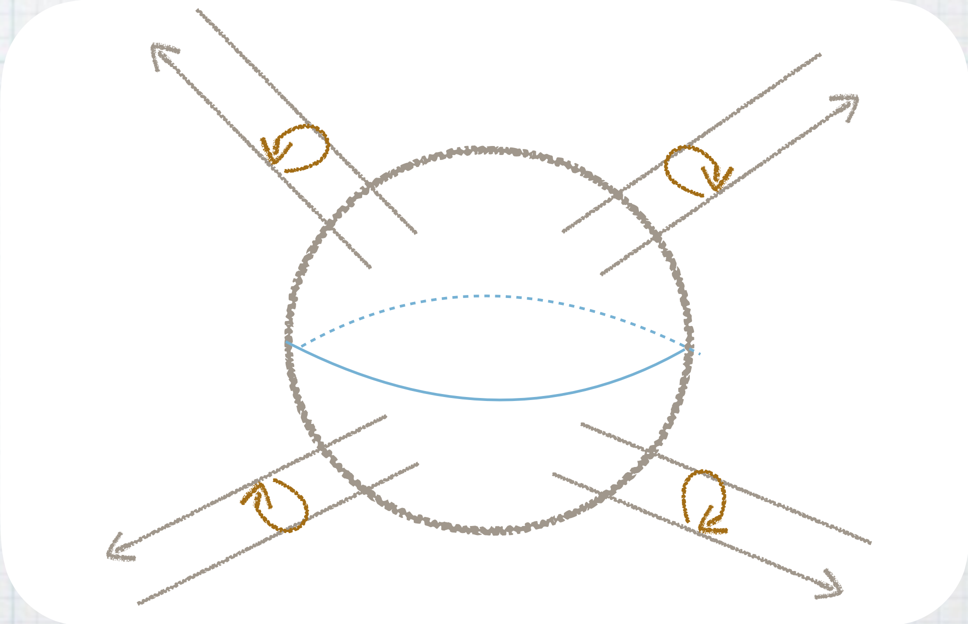




q-deformed spin networks for curved vertices

- Non-abelian closure constraint $G_1 G_2 .. G_V = \mathbb{I}$
- Use holonomies on surface as « fluxes »
- Use complex « Immirzi parameter »
- Infinite superposition of little loops ?

double spin networks
or spin tubes
or Drinfeld tubes



& the « loop gravity string »
or CFT bubbles

Coarse-Graining Spin Networks

Some new rich structures for LQG to explore ...

Coarse-Graining Spin Networks

Some new rich structures for LQG to explore ...

Let's Holo-Grain them !

Coarse-Graining

Physics of QG

Holographic Principle

Coarse-Graining Spin Networks

Project spin network data on boundary surfaces...

... Bubble Networks ?

Coarse-graining flow from bulk state to surface state ?

Holographic grains ?

Some new rich structures for LQG to explore ...

Holo-grains ... or Holo-bubbles ?

Bulk locality from boundary non-locality ?

Coarse-graining bubble networks

Let's Holo-Grain them !

Implement holography by coarse-graining ?

Diving into the bubbles

Define CFT on bubbles

Bubble-Merging algebra as diffeo's ?

and how to glue the bubble CFTs ?

Coarse-graining inv as diffeo's ?

TQFT -> CFT

Coarse-graining flow from surface state to surface state ?

Deform the bubbles or diffeo the bubbles ?

Thank you for your attention !