

THE GROUP FIELD THEORY APPROACH TO QUANTUM GRAVITY: A QFT FOR THE MICROSTRUCTURE OF SPACETIME

Daniele Oriti

Max Planck Institute for Gravitational Physics (Albert Einstein Institute)
Golm, Germany, EU

FQXI conference, Ponta Delgada, 10/07/2009



QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- Quantum Gravity not so much a quantization of GR, but a microscopic quantum theory of the spacetime structure (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → a QFT for quantum gravity?
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- Quantum Gravity not so much a quantization of GR, but a microscopic quantum theory of the spacetime structure (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → a QFT for quantum gravity?
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- **Quantum Gravity** not so much a quantization of GR, but a **microscopic quantum theory of the spacetime structure** (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → **a QFT for quantum gravity?**
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- Quantum Gravity not so much a quantization of GR, but a microscopic quantum theory of the spacetime structure (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → a QFT for quantum gravity?
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- Quantum Gravity not so much a quantization of GR, but a microscopic quantum theory of the spacetime structure (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → a QFT for quantum gravity?
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- Quantum Gravity not so much a quantization of GR, but a microscopic quantum theory of the spacetime structure (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → a QFT for quantum gravity?
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

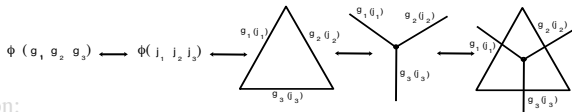
- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- Quantum Gravity not so much a quantization of GR, but a microscopic quantum theory of the spacetime structure (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → a QFT for quantum gravity?
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

QUANTUM GRAVITY AS A QFT FOR THE “ATOMS OF SPACE”?

- Main lesson from GR: “Gravity is spacetime geometry”, thus spacetime is itself a physical system
- Quantum Gravity not so much a quantization of GR, but a microscopic quantum theory of the spacetime structure (“atomic theory of space”)
- QFT is best formalism we have for microscopic physics (particle and atomic physics, condensed matter,...) → a QFT for quantum gravity?
- A QFT on which space?
 - QG should explain origin and properties of spacetime itself (geometry and topology?) → background independence!
 - it can be only be a QFT on some auxiliary, internal or “meta-space”
- a QFT of what? what are the fundamental quanta?
 - quanta of space itself! fundamental excitations of space around the vacuum (nothing = not even space)

GFT BASICS

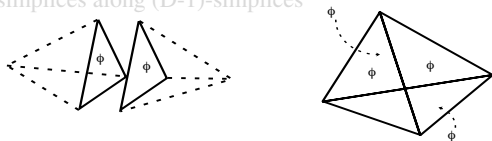
- complex field ϕ over D copies of a group manifold G (e.g. Lorentz group, for QG): $\phi(g_1, \dots, g_D) : \underbrace{G \times \dots \times G}_D \rightarrow \mathbb{C}$
- field can be expanded in modes j (irreducible representations of G)
- $\phi \simeq$ building block of quantum geometry - $(D-1)$ -simplex or spin network vertex



- field action:

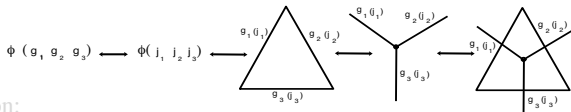
$$S_D(\phi, \lambda) = \int dg_i d\tilde{g}_i \phi(g_i) \mathcal{K}(g_i, \tilde{g}_i^{-1}) \phi(\tilde{g}_i) + \lambda \int dg_{ij} \phi(g_{ij}) \dots \phi(g_{D+ij}) \mathcal{V}(g_{ij})$$

- combinatorics of arguments in \mathcal{V} reflects gluing of $(D-2)$ -faces in a D -simplex, $\mathcal{K} \rightarrow$ gluing of D -simplices along $(D-1)$ -simplices



GFT BASICS

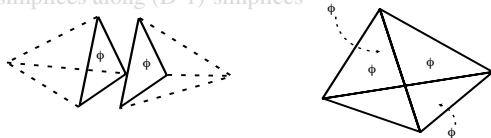
- complex field ϕ over D copies of a group manifold G (e.g. Lorentz group, for QG): $\phi(g_1, \dots, g_D) : \underbrace{G \times \dots \times G}_D \rightarrow \mathbb{C}$
- field can be expanded in modes j (irreducible representations of G)
- $\phi \simeq$ building block of quantum geometry - (D-1)-simplex or spin network vertex



- field action:

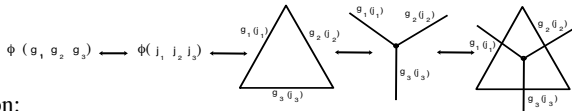
$$S_D(\phi, \lambda) = \int dg_i d\tilde{g}_i \phi(g_i) \mathcal{K}(g_i, \tilde{g}_i^{-1}) \phi(\tilde{g}_i) + \lambda \int dg_{ij} \phi(g_{ij}) \dots \phi(g_{D+ij}) \mathcal{V}(g_{ij})$$

- combinatorics of arguments in \mathcal{V} reflects gluing of (D-2)-faces in a D-simplex, $\mathcal{K} \rightarrow$ gluing of D-simplices along (D-1)-simplices



GFT BASICS

- complex field ϕ over D copies of a group manifold G (e.g. Lorentz group, for QG): $\phi(g_1, \dots, g_D) : \underbrace{G \times \dots \times G}_D \rightarrow \mathbb{C}$
- field can be expanded in modes j (irreducible representations of G)
- $\phi \simeq$ building block of quantum geometry - (D-1)-simplex or spin network vertex



- field action:

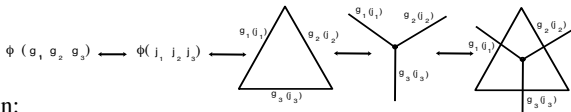
$$S_D(\phi, \lambda) = \int dg_i d\tilde{g}_i \phi(g_i) \mathcal{K}(g_i, \tilde{g}_i^{-1}) \phi(\tilde{g}_i) + \lambda \int dg_{ij} \phi(g_{1j}) \dots \phi(g_{D+1j}) \mathcal{V}(g_{ij})$$

- combinatorics of arguments in \mathcal{V} reflects gluing of (D-2)-faces in a D-simplex, $\mathcal{K} \rightarrow$ gluing of D-simplices along (D-1)-simplices



GFT BASICS

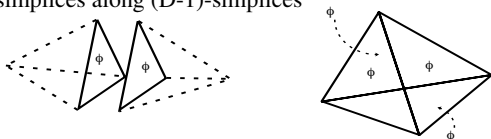
- complex field ϕ over D copies of a group manifold G (e.g. Lorentz group, for QG): $\phi(g_1, \dots, g_D) : \underbrace{G \times \dots \times G}_D \rightarrow \mathbb{C}$
- field can be expanded in modes j (irreducible representations of G)
- $\phi \simeq$ building block of quantum geometry - (D-1)-simplex or spin network vertex



- field action:

$$S_D(\phi, \lambda) = \int dg_i d\tilde{g}_i \phi(g_i) \mathcal{K}(g_i, \tilde{g}_i^{-1}) \phi(\tilde{g}_i) + \lambda \int dg_{ij} \phi(g_{1j}) \dots \phi(g_{D+1j}) \mathcal{V}(g_{ij})$$

- combinatorics of arguments in \mathcal{V} reflects gluing of (D-2)-faces in a D-simplex, $\mathcal{K} \rightarrow$ gluing of D-simplices along (D-1)-simplices



GFT BASICS

- quantum theory: Feynman expansion of the partition function:

$$Z = \int \mathcal{D}\phi e^{iS[\phi]} = \sum_{\Gamma} \frac{\lambda^{N_{\Gamma}}}{\text{sym}[\Gamma]} Z(\Gamma)$$

- Feynman diagrams Γ are simplicial complexes of arbitrary topology
- $Z(\Gamma) \simeq$ discrete and algebraic (only group and representation theory) QG path integral $\rightarrow Z(\Gamma) \simeq \int \mathcal{D}g_{\Gamma} e^{iS_{\Gamma}(g)}$
- Quantum Gravity formulated as a sum over simplicial complexes (discrete spacetimes) of all topologies, as interaction processes, weighted by a simplicial gravity path integral formulated in algebraic terms

GFT BASICS

- quantum theory: Feynman expansion of the partition function:

$$Z = \int \mathcal{D}\phi e^{iS[\phi]} = \sum_{\Gamma} \frac{\lambda^{N_{\Gamma}}}{\text{sym}[\Gamma]} Z(\Gamma)$$

- Feynman diagrams Γ are simplicial complexes of arbitrary topology
- $Z(\Gamma) \simeq$ discrete and algebraic (only group and representation theory) QG path integral $\rightarrow Z(\Gamma) \simeq \int \mathcal{D}g_{\Gamma} e^{iS_{\Gamma}(g)}$
- Quantum Gravity formulated as a sum over simplicial complexes (discrete spacetimes) of all topologies, as interaction processes, weighted by a simplicial gravity path integral formulated in algebraic terms

GFT BASICS

- quantum theory: Feynman expansion of the partition function:

$$Z = \int \mathcal{D}\phi e^{iS[\phi]} = \sum_{\Gamma} \frac{\lambda^{N_{\Gamma}}}{\text{sym}[\Gamma]} Z(\Gamma)$$

- Feynman diagrams Γ are simplicial complexes of arbitrary topology
- $Z(\Gamma) \simeq$ discrete and algebraic (only group and representation theory) QG path integral $\rightarrow Z(\Gamma) \simeq \int \mathcal{D}g_{\Gamma} e^{iS_{\Gamma}(g)}$
- Quantum Gravity formulated as a sum over simplicial complexes (discrete spacetimes) of all topologies, as interaction processes, weighted by a simplicial gravity path integral formulated in algebraic terms

GFT BASICS

- quantum theory: Feynman expansion of the partition function:

$$Z = \int \mathcal{D}\phi e^{iS[\phi]} = \sum_{\Gamma} \frac{\lambda^{N_{\Gamma}}}{\text{sym}[\Gamma]} Z(\Gamma)$$

- Feynman diagrams Γ are simplicial complexes of arbitrary topology
- $Z(\Gamma) \simeq$ discrete and algebraic (only group and representation theory) QG path integral $\rightarrow Z(\Gamma) \simeq \int \mathcal{D}g_{\Gamma} e^{iS_{\Gamma}(g)}$
- Quantum Gravity formulated as a sum over simplicial complexes (discrete spacetimes) of all topologies, as interaction processes, weighted by a simplicial gravity path integral formulated in algebraic terms

CONVERGENCE OF APPROACHES...UNITED WE STAND!!!

- GFT can be common, unifying framework for various QG approaches:
 - Loop Quantum Gravity and spin foam models:
 - GFT states are Spin Networks, the quantum states of geometry as identified by LQG
 - GFT Feynman amplitudes are Spin Foam models (sum over histories of spin networks)
 - Quantum Regge Calculus: a single GFT Feynman amplitude defines discrete QG path integral (related to Regge theory in various ways)
 - Dynamical Triangulations: GFT describes QG (perturbatively) as sum over triangulations, weighted by discrete action
 -plus ideas and tools from non-commutative geometry
- At the same time, GFTs offer new tools, and a new perspective on continuum/classical approximation.....

CONVERGENCE OF APPROACHES...UNITED WE STAND!!!

- GFT can be common, unifying framework for various QG approaches:
 - **Loop Quantum Gravity and spin foam models:**
 - GFT states are Spin Networks, the quantum states of geometry as identified by LQG
 - GFT Feynman amplitudes are Spin Foam models (sum over histories of spin networks)
 - **Quantum Regge Calculus:** a single GFT Feynman amplitude defines discrete QG path integral (related to Regge theory in various ways)
 - **Dynamical Triangulations:** GFT describes QG (perturbatively) as sum over triangulations, weighted by discrete action
 -plus ideas and tools from **non-commutative geometry**
- At the same time, GFTs offer new tools, and a new perspective on continuum/classical approximation.....

CONVERGENCE OF APPROACHES...UNITED WE STAND!!!

- GFT can be common, unifying framework for various QG approaches:
 - **Loop Quantum Gravity and spin foam models:**
 - GFT states are Spin Networks, the quantum states of geometry as identified by LQG
 - GFT Feynman amplitudes are Spin Foam models (sum over histories of spin networks)
 - **Quantum Regge Calculus:** a single GFT Feynman amplitude defines discrete QG path integral (related to Regge theory in various ways)
 - **Dynamical Triangulations:** GFT describes QG (perturbatively) as sum over triangulations, weighted by discrete action
 -plus ideas and tools from **non-commutative geometry**
- At the same time, GFTs offer new tools, and a new perspective on continuum/classical approximation.....

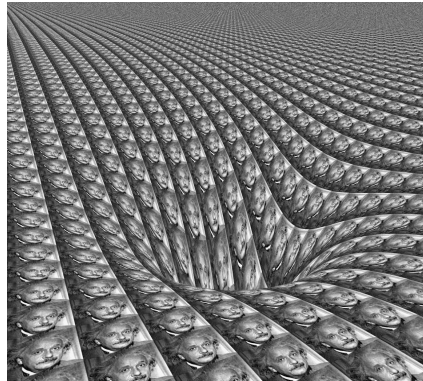
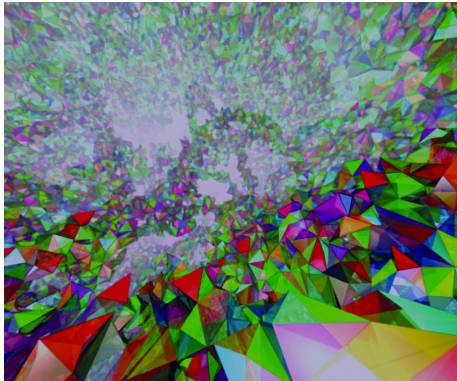
CONVERGENCE OF APPROACHES...UNITED WE STAND!!!

- GFT can be common, unifying framework for various QG approaches:
 - **Loop Quantum Gravity and spin foam models:**
 - GFT states are Spin Networks, the quantum states of geometry as identified by LQG
 - GFT Feynman amplitudes are Spin Foam models (sum over histories of spin networks)
 - **Quantum Regge Calculus:** a single GFT Feynman amplitude defines discrete QG path integral (related to Regge theory in various ways)
 - **Dynamical Triangulations:** GFT describes QG (perturbatively) as sum over triangulations, weighted by discrete action
 -plus ideas and tools from **non-commutative geometry**
- At the same time, GFTs offer new tools, and a new perspective on continuum/classical approximation.....

CONVERGENCE OF APPROACHES...UNITED WE STAND!!!

- GFT can be common, unifying framework for various QG approaches:
 - **Loop Quantum Gravity and spin foam models:**
 - GFT states are Spin Networks, the quantum states of geometry as identified by LQG
 - GFT Feynman amplitudes are Spin Foam models (sum over histories of spin networks)
 - **Quantum Regge Calculus:** a single GFT Feynman amplitude defines discrete QG path integral (related to Regge theory in various ways)
 - **Dynamical Triangulations:** GFT describes QG (perturbatively) as sum over triangulations, weighted by discrete action
 -plus ideas and tools from **non-commutative geometry**
- At the same time, GFTs offer new tools, and a new perspective on continuum/classical approximation.....

PROBLEM OF THE CONTINUUM IN DISCRETE QG: CONTINUUM GEOMETRY FROM ATOMS OF SPACE?



WHENCE THE CONTINUUM?

- **GFT as fundamental (atomic) theory for the micro-structure of quantum space**
- study the corresponding “many particle” regime
- ideas and tools from condensed matter theory and analog gravity models:
 - spacetime as a quantum condensate/liquid phase of fundamental discrete constituents + geometry as an emergent concept
- SO:
 - study GFT phases and phase transitions \rightarrow geometrogenesis as GFT condensation?
 - continuum spacetime \equiv fluid phase, i.e. intertwiners/(D-1)-simplices condense to form a fluid-continuum
 - continuum geometry emerges in condensed phase, as the hydrodynamic variables in the (super)fluid phase of ordinary condensed matter systems
 - (modified) General Relativity from GFT hydrodynamics?

WHENCE THE CONTINUUM?

- **GFT as fundamental (atomic) theory for the micro-structure of quantum space**
- study the corresponding “many particle” regime
- ideas and tools from condensed matter theory and analog gravity models:
 - spacetime as a quantum condensate/liquid phase of fundamental discrete constituents + geometry as an emergent concept
- SO:
 - study GFT phases and phase transitions → **geometrogenesis as GFT condensation?**
 - **continuum spacetime \equiv fluid phase, i.e. intertwiners/(D-1)-simplices condense to form a fluid-continuum**
 - **continuum geometry emerges in condensed phase, as the hydrodynamic variables in the (super)fluid phase of ordinary condensed matter systems**
 - **(modified) General Relativity from GFT hydrodynamics?**

WHENCE THE CONTINUUM?

- **GFT as fundamental (atomic) theory for the micro-structure of quantum space**
- study the corresponding “many particle” regime
- ideas and tools from condensed matter theory and analog gravity models:
 - spacetime as a quantum condensate/liquid phase of fundamental discrete constituents + geometry as an emergent concept
- SO:
 - study GFT phases and phase transitions → *geometrogenesis as GFT condensation?*
 - *continuum spacetime \equiv fluid phase, i.e. intertwiners/(D-1)-simplices condense to form a fluid-continuum*
 - *continuum geometry emerges in condensed phase, as the hydrodynamic variables in the (super)fluid phase of ordinary condensed matter systems*
 - *(modified) General Relativity from GFT hydrodynamics?*

WHENCE THE CONTINUUM?

- **GFT as fundamental (atomic) theory for the micro-structure of quantum space**
- study the corresponding “many particle” regime
- ideas and tools from condensed matter theory and analog gravity models:
 - spacetime as a quantum condensate/liquid phase of fundamental discrete constituents + geometry as an emergent concept
- SO:
 - study GFT phases and phase transitions → **geometrogenesis as GFT condensation?**
 - **continuum spacetime \equiv fluid phase, i.e. intertwiners/(D-1)-simplices condense to form a fluid-continuum**
 - continuum geometry emerges in condensed phase, as the hydrodynamic variables in the (super)fluid phase of ordinary condensed matter systems
 - **(modified) General Relativity from GFT hydrodynamics?**

WHENCE THE CONTINUUM?

- **GFT as fundamental (atomic) theory for the micro-structure of quantum space**
- study the corresponding “many particle” regime
- ideas and tools from condensed matter theory and analog gravity models:
 - spacetime as a quantum condensate/liquid phase of fundamental discrete constituents + geometry as an emergent concept
- SO:
 - study GFT phases and phase transitions → **geometrogenesis as GFT condensation?**
 - **continuum spacetime \equiv fluid phase, i.e. intertwiners/(D-1)-simplices condense to form a fluid-continuum**
 - continuum geometry emerges in condensed phase, as the hydrodynamic variables in the (super)fluid phase of ordinary condensed matter systems
 - (modified) General Relativity from GFT hydrodynamics?

WHENCE THE CONTINUUM?

- **GFT as fundamental (atomic) theory for the micro-structure of quantum space**
- study the corresponding “many particle” regime
- ideas and tools from condensed matter theory and analog gravity models:
 - spacetime as a quantum condensate/liquid phase of fundamental discrete constituents + geometry as an emergent concept
- SO:
 - study GFT phases and phase transitions → **geometrogenesis as GFT condensation?**
 - **continuum spacetime \equiv fluid phase, i.e. intertwiners/(D-1)-simplices condense to form a fluid-continuum**
 - continuum geometry emerges in condensed phase, as the hydrodynamic variables in the (super)fluid phase of ordinary condensed matter systems
 - (modified) General Relativity from GFT hydrodynamics?

WHENCE THE CONTINUUM?

- **GFT as fundamental (atomic) theory for the micro-structure of quantum space**
- study the corresponding “many particle” regime
- ideas and tools from condensed matter theory and analog gravity models:
 - spacetime as a quantum condensate/liquid phase of fundamental discrete constituents + geometry as an emergent concept
- SO:
 - study GFT phases and phase transitions → **geometrogenesis as GFT condensation?**
 - **continuum spacetime \equiv fluid phase, i.e. intertwiners/(D-1)-simplices condense to form a fluid-continuum**
 - continuum geometry emerges in condensed phase, as the hydrodynamic variables in the (super)fluid phase of ordinary condensed matter systems
 - **(modified) General Relativity from GFT hydrodynamics?**

THE EMERGENCE OF CONTINUUM SPACETIME AND GEOMETRY



Microscopic GFT
(LQG, Simplicial QG)



Statistical GFT → GFT fluid, GFT hydrodynamics



Effective continuum spacetime and geometry

(modified) GR
astrophysics, particle physics, cosmology

THE EMERGENCE OF CONTINUUM SPACETIME AND GEOMETRY



Microscopic GFT
(LQG, Simplicial QG)



Statistical GFT → GFT fluid, GFT hydrodynamics



Effective continuum spacetime and geometry

(modified) GR
astrophysics, particle physics, cosmology

MESSAGES:

- Quantum Space could be understood as a “background independent condensed matter system”
- Group Field Theories are a candidate microscopic description of the properties and dynamics of the atoms of space, in simplicial, algebraic language
- GFTs are unifying framework for discrete approaches to quantum gravity
- continuum spacetime is a fluid of GFT quanta, and geometry emerges as a collective, effective variable in the fluid phase
- (modified) GR emerges from GFT hydrodynamics
- in progress.....so.....stay tuned!