Quantum gravity at the corner

Marc Geiller
ENS de Lyon

Workshop “Théorie, Univers et Gravitation”
IHP, December 13th–15th 2021

Motivations

Quantum gravity

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**
- Certain **extra features appear on boundaries**: charges, algebras, degrees of freedom

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**
- Certain **extra features appear on boundaries**: charges, algebras, degrees of freedom
- This contains **important information for the classical theory**

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**
- Certain **extra features appear on boundaries**: charges, algebras, degrees of freedom
- This contains **important information for the classical theory**
- It also lays the **foundations for the quantum theory**, and reveals new insights

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**
- Certain **extra features appear on boundaries**: charges, algebras, degrees of freedom
- This contains **important information for the classical theory**
- It also lays the **foundations for the quantum theory**, and reveals new insights

Quantum gravity at the corner

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**
- Certain **extra features appear on boundaries**: charges, algebras, degrees of freedom
- This contains **important information for the classical theory**
- It also lays the **foundations for the quantum theory**, and reveals new insights

Quantum gravity at the corner

- Proposal based on **local holography** (as opposed to AdS and celestial holographies)

Motivations

Quantum gravity

- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**
- Certain **extra features appear on boundaries**: charges, algebras, degrees of freedom
- This contains **important information for the classical theory**
- It also lays the **foundations for the quantum theory**, and reveals new insights

Quantum gravity at the corner

- Proposal based on **local holography** (as opposed to AdS and celestial holographies)
- Assign Hilbert spaces, states, irreps., to local subregions based on symmetry algebras

Motivations

Quantum gravity

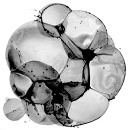
- What are the fundamental degrees of freedom, and where do they live?
- We can make educated guesses, or follow guidance from the classical theory
- A powerful concept is that of symmetries, but **what are the symmetries of gravity?**

Gauge theories in bounded regions

- General relativity is a diffeomorphism-invariant gauge theory
- Gauge is more than redundancy, it controls the **coupling of subsystems**
- Certain **extra features appear on boundaries**: charges, algebras, degrees of freedom
- This contains **important information for the classical theory**
- It also lays the **foundations for the quantum theory**, and reveals new insights

Quantum gravity at the corner

- Proposal based on **local holography** (as opposed to AdS and celestial holographies)
- Assign Hilbert spaces, states, irreps., to local subregions based on symmetry algebras
- **Why and how?**



Modern version of Noether's theorems

Symmetries of gravity

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, . . .

Symmetries of gravity

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, . . .
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, . . .

Symmetries of gravity

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, ...
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, ...
- Basic ingredient is the symplectic potential θ, which is the boundary term in

$$\delta L = (\text{Euler–Lagrange})\,\delta\phi + d\theta$$

Symmetries of gravity

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, ...
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, ...
- Basic ingredient is the symplectic potential θ, which is the boundary term in

$$\delta L = (\text{Euler–Lagrange})\,\delta\phi + d\theta$$

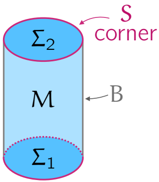
- It enables to ask questions like: What is the generator of a diffeomorphism along ξ?

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, . . .
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, . . .
- Basic ingredient is the symplectic potential θ, which is the boundary term in

$$\delta L = (\text{Euler–Lagrange})\,\delta\phi + d\theta$$

- It enables to ask questions like: What is the generator of a diffeomorphism along ξ?



$$\not{\delta} H[\xi] \approx \oint_S \delta Q - \xi \cdot \theta$$

Q = Noether charge

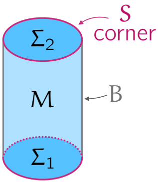
Symmetries of gravity

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, ...
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, ...
- Basic ingredient is the symplectic potential θ, which is the boundary term in

$$\delta L = (\text{Euler–Lagrange})\,\delta\phi + \mathrm{d}\theta$$

- It enables to ask questions like: What is the generator of a diffeomorphism along ξ?



$$\not{\delta} H[\xi] \approx \oint_S \delta Q - \xi \cdot \theta$$

$Q =$ Noether charge

- **Non-trivial information about a 3d region Σ is encoded on its 2d boundary S**

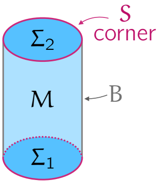
Symmetries of gravity

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, ...
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, ...
- Basic ingredient is the symplectic potential θ, which is the boundary term in

$$\delta L = (\text{Euler–Lagrange})\,\delta\phi + d\theta$$

- It enables to ask questions like: What is the generator of a diffeomorphism along ξ?



$$\delta\!\!\!/ H[\xi] \approx \oint_S \delta Q - \xi \cdot \theta$$

$Q =$ Noether charge

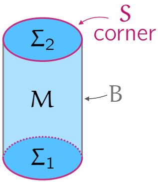
- **Non-trivial information about a 3d region Σ is encoded on its 2d boundary S**
- Many subtleties

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, ...
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, ...
- Basic ingredient is the symplectic potential θ, which is the boundary term in

$$\delta L = (\text{Euler–Lagrange})\,\delta\phi + d\theta$$

- It enables to ask questions like: What is the generator of a diffeomorphism along ξ?



$$\not{\delta} H[\xi] \approx \oint_S \delta Q - \xi \cdot \theta$$

Q = Noether charge

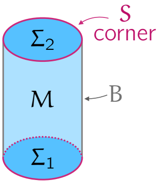
- **Non-trivial information about a 3d region Σ is encoded on its 2d boundary S**
- Many subtleties
  - the charges are not necessarily finite, nor integrable, nor conserved

Modern version of Noether's theorems

- **Covariant phase space formalism**, due to Anderson, Ashtekar, Barnich, Brandt, Compère, Crnkovic, Henneaux, Iyer, Kijowski, Lee, Wald, Witten, Zoupas, ...
- Extended recently by Barnich, Chandrasekaran, Compère, Fiorucci, Flanagan, Freidel, MG, Harlow, Oliveri, Pranzetti, Riello, Ruzziconi, Speranza, Speziale, Troessaert, Wu, Zwikel, ...
- Basic ingredient is the symplectic potential θ, which is the boundary term in

$$\delta L = (\text{Euler–Lagrange})\,\delta\phi + d\theta$$

- It enables to ask questions like: What is the generator of a diffeomorphism along ξ?



$$\not{\delta} H[\xi] \approx \oint_S \delta Q - \xi \cdot \theta$$

Q = Noether charge

- **Non-trivial information about a 3d region Σ is encoded on its 2d boundary S**
- Many subtleties
  - the charges are not necessarily finite, nor integrable, nor conserved
  - depends on B and what happens there (boundary conditions, radiation flux, ...)

Algebraic structures

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi],\mathrm{H}[\zeta]\big\}=\mathrm{H}[\xi,\zeta]+\mathrm{C}[\xi,\zeta]$$

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi], \mathrm{H}[\zeta]\big\} = \mathrm{H}[\xi, \zeta] + \mathrm{C}[\xi, \zeta]$$

- When H is not integrable we get

$$\delta_\xi \mathrm{H}[\zeta] = \mathrm{H}[\xi, \zeta] + \delta_\xi \mathrm{F}[\zeta]$$

$$\text{evolution} = \text{rotation} + \text{dissipation}$$

Symmetries of gravity

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi],\mathrm{H}[\zeta]\big\}=\mathrm{H}[\xi,\zeta]+\mathrm{C}[\xi,\zeta]$$

- When H is not integrable we get

$$\delta_\xi\mathrm{H}[\zeta]=\mathrm{H}[\xi,\zeta]+\delta_\xi\mathrm{F}[\zeta]$$
$$\text{evolution}=\text{rotation}+\text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi],\mathrm{H}[\zeta]\big\}=\mathrm{H}[\xi,\zeta]+\mathrm{C}[\xi,\zeta]$$

- When H is not integrable we get

$$\delta_\xi\mathrm{H}[\zeta]=\mathrm{H}[\xi,\zeta]+\delta_\xi\mathrm{F}[\zeta]$$
$$\text{evolution}=\text{rotation}+\text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary
- **True for any gauge theory**, e.g. U(1) Chern–Simons (“less is more”)

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{H[\xi],H[\zeta]\big\}=H[\xi,\zeta]+C[\xi,\zeta]$$

- When H is not integrable we get

$$\delta_\xi H[\zeta]=H[\xi,\zeta]+\delta_\xi F[\zeta]$$
$$\text{evolution}=\text{rotation}+\text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary
- **True for any gauge theory**, e.g. U(1) Chern–Simons (“less is more”)

Asymptotic symmetries

Symmetries of gravity

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi],\mathrm{H}[\zeta]\big\}=\mathrm{H}[\xi,\zeta]+\mathrm{C}[\xi,\zeta]$$

- When H is not integrable we get

$$\delta_\xi\mathrm{H}[\zeta]=\mathrm{H}[\xi,\zeta]+\delta_\xi\mathrm{F}[\zeta]$$
$$\text{evolution}=\text{rotation}+\text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary
- **True for any gauge theory**, e.g. U(1) Chern–Simons (“less is more”)

Asymptotic symmetries

- A lot is known about **symmetries of asymptotic boundaries**

Symmetries of gravity

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi],\mathrm{H}[\zeta]\big\}=\mathrm{H}[\xi,\zeta]+\mathrm{C}[\xi,\zeta]$$

- When H is not integrable we get

$$\delta_\xi\mathrm{H}[\zeta]=\mathrm{H}[\xi,\zeta]+\delta_\xi\mathrm{F}[\zeta]$$
$$\text{evolution}=\text{rotation}+\text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary
- **True for any gauge theory**, e.g. U(1) Chern–Simons (“less is more”)

Asymptotic symmetries

- A lot is known about **symmetries of asymptotic boundaries**
  - asymptotically AdS_3 and double Virasoro symmetry (AdS/CFT)

Symmetries of gravity

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi],\mathrm{H}[\zeta]\big\}=\mathrm{H}[\xi,\zeta]+\mathrm{C}[\xi,\zeta]$$

- When H is not integrable we get

$$\delta_\xi\mathrm{H}[\zeta]=\mathrm{H}[\xi,\zeta]+\delta_\xi\mathrm{F}[\zeta]$$
$$\text{evolution}=\text{rotation}+\text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary
- **True for any gauge theory**, e.g. U(1) Chern–Simons (“less is more”)

Asymptotic symmetries

- A lot is known about **symmetries of asymptotic boundaries**
  - asymptotically AdS_3 and double Virasoro symmetry (AdS/CFT)
  - asymptotically flat spacetimes and BMS symmetry (celestial/null holography)

Symmetries of gravity

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{\mathrm{H}[\xi],\mathrm{H}[\zeta]\big\}=\mathrm{H}[\xi,\zeta]+\mathrm{C}[\xi,\zeta]$$

- When H is not integrable we get

$$\delta_\xi\mathrm{H}[\zeta]=\mathrm{H}[\xi,\zeta]+\delta_\xi\mathrm{F}[\zeta]$$
$$\text{evolution}=\text{rotation}+\text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary
- **True for any gauge theory**, e.g. U(1) Chern–Simons ("less is more")

Asymptotic symmetries

- A lot is known about **symmetries of asymptotic boundaries**
  - asymptotically AdS_3 and double Virasoro symmetry (AdS/CFT)
  - asymptotically flat spacetimes and BMS symmetry (celestial/null holography)
- Extensions of BMS_4 and BMS_3 (e.g. including Weyl) have been proposed by Barnich, Campiglia, Compère, Fiorucci, Flanagan, Freidel, MG, Goeller, Laddha, Nichols, Ruzziconi, Troessaert, Oliveri, Peraza, Prabhu, Pranzetti, Speziale, Zwikel, . . .

Symmetries of gravity

Algebraic structures

- When H is integrable, we get a projective representation

$$\big\{H[\xi], H[\zeta]\big\} = H[\xi, \zeta] + C[\xi, \zeta]$$

- When H is not integrable we get

$$\delta_\xi H[\zeta] = H[\xi, \zeta] + \delta_\xi F[\zeta]$$
$$\text{evolution} = \text{rotation} + \text{dissipation}$$

- These algebras are **infinite-dimensional**, and can be associated to any boundary
- **True for any gauge theory**, e.g. U(1) Chern–Simons ("less is more")

Asymptotic symmetries

- A lot is known about **symmetries of asymptotic boundaries**
  - asymptotically AdS_3 and double Virasoro symmetry (AdS/CFT)
  - asymptotically flat spacetimes and BMS symmetry (celestial/null holography)
- Extensions of BMS_4 and BMS_3 (e.g. including Weyl) have been proposed by Barnich, Campiglia, Compère, Fiorucci, Flanagan, Freidel, MG, Goeller, Laddha, Nichols, Ruzziconi, Troessaert, Oliveri, Peraza, Prabhu, Pranzetti, Speziale, Zwikel, . . .
- Related to **memory observables** and **IR regime of gauge theories** [Strominger, . . .]

Entanglement of subregions

Local subsystems

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$

Local subsystems

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$
- In non-relativistic QFT we have

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad\qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle = 0$$

Local subsystems

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$
- In non-relativistic QFT we have

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad\qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle = 0$$

- In relativistic QFT we have vacuum entanglement, and

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad\qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle \neq 0$$

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$
- In non-relativistic QFT we have

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle = 0$$

- In relativistic QFT we have vacuum entanglement, and

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle \neq 0$$

- In gauge theory the Hilbert spaces don't even factorize [Buividovich, Casini, Das, Datta, Donnelly, Ghosh, Huerta, Ishibashi, Matsuura, Polikarpov, Ryu, Soni, Trivedi, Wall, Wen, . . .]

$$\mathcal{H} \supset \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}}$$

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$
- In non-relativistic QFT we have

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle = 0$$

- In relativistic QFT we have vacuum entanglement, and

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle \neq 0$$

- In gauge theory the Hilbert spaces don't even factorize [Buividovich, Casini, Das, Datta, Donnelly, Ghosh, Huerta, Ishibashi, Matsuura, Polikarpov, Ryu, Soni, Trivedi, Wall, Wen, . . .]

$$\mathcal{H} \supset \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}}$$

- What is missing?

Local subsystems

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$
- In non-relativistic QFT we have

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle = 0$$

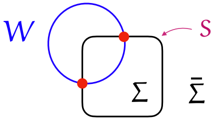
- In relativistic QFT we have vacuum entanglement, and

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle \neq 0$$

- In gauge theory the Hilbert spaces don't even factorize [Buividovich, Casini, Das, Datta, Donnelly, Ghosh, Huerta, Ishibashi, Matsuura, Polikarpov, Ryu, Soni, Trivedi, Wall, Wen, . . .]

$$\mathcal{H} \supset \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}}$$

- What is missing? Gauge-invariant observables crossing the boundary



Local subsystems

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$
- In non-relativistic QFT we have

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle = 0$$

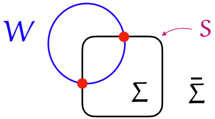
- In relativistic QFT we have vacuum entanglement, and

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle \neq 0$$

- In gauge theory the Hilbert spaces don't even factorize [Buividovich, Casini, Das, Datta, Donnelly, Ghosh, Huerta, Ishibashi, Matsuura, Polikarpov, Ryu, Soni, Trivedi, Wall, Wen, . . .]

$$\mathcal{H} \supset \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}}$$

- What is missing? Gauge-invariant observables crossing the boundary



- To describe subregions we should extend the Hilbert space to $\mathcal{H}_{\text{ext}} = \mathcal{H}_\Sigma \otimes \mathcal{H}_S$

Local subsystems

Entanglement of subregions

- Consider a spatial region Σ and its complement $\bar{\Sigma}$
- In non-relativistic QFT we have

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle = 0$$

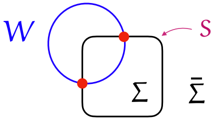
- In relativistic QFT we have vacuum entanglement, and

$$\mathcal{H} = \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}} \qquad \langle \Psi_\Sigma | \Psi_{\bar{\Sigma}} \rangle \neq 0$$

- In gauge theory the Hilbert spaces don't even factorize [Buividovich, Casini, Das, Datta, Donnelly, Ghosh, Huerta, Ishibashi, Matsuura, Polikarpov, Ryu, Soni, Trivedi, Wall, Wen, . . .]

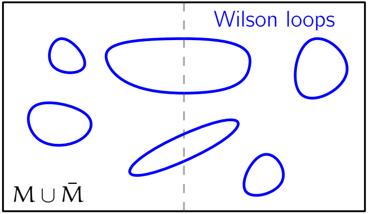
$$\mathcal{H} \supset \mathcal{H}_\Sigma \otimes \mathcal{H}_{\bar{\Sigma}}$$

- What is missing? Gauge-invariant observables crossing the boundary



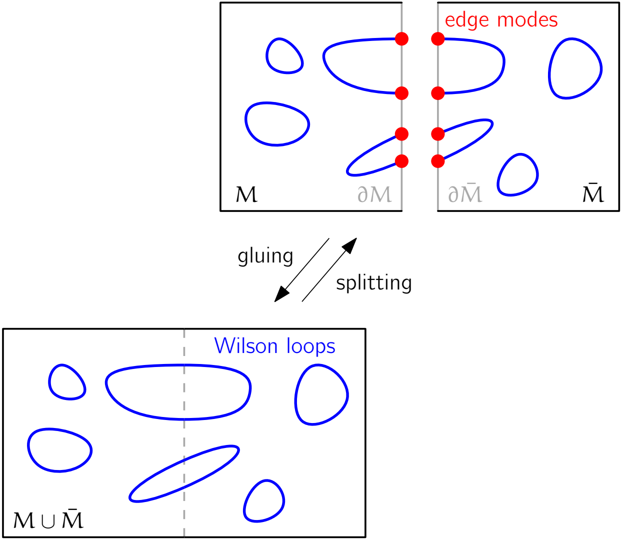
- To describe subregions we should extend the Hilbert space to $\mathcal{H}_{\text{ext}} = \mathcal{H}_\Sigma \otimes \mathcal{H}_S$
- $\mathcal{H}_S$ should carry a **representation of the local corner symmetry group**

Local subsystems



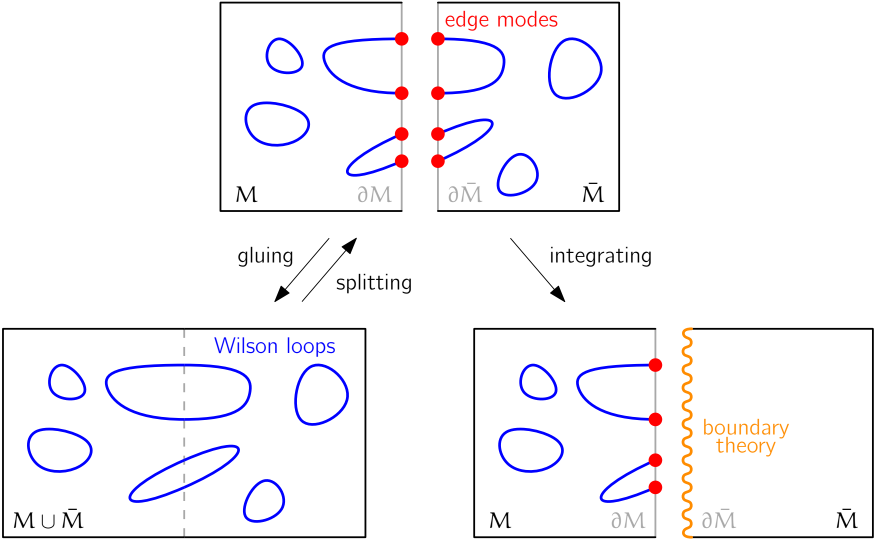
[Agarwal, Blommaert, Carlip, Carrozza, MG, Gomes, Hoehn, Jai-akson, Karabali, Mertens, Nair, Pretko, Riello, Verschelde, . . .]

Local subsystems



[Agarwal, Blommaert, Carlip, Carrozza, MG, Gomes, Hoehn, Jai-akson, Karabali, Mertens, Nair, Pretko, Riello, Verschelde, . . .]

Local subsystems



[Agarwal, Blommaert, Carlip, Carrozza, MG, Gomes, Hoehn, Jai-akson, Karabali, Mertens, Nair, Pretko, Riello, Verschelde, . . .]

Corner symmetry group of gravity

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G &= \quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ &= \big(\text{Diff}(S) \ltimes H\big) \ltimes G_{\text{dynamical}} \end{aligned}$$

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G = &\quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ = &\left(\text{Diff}(S) \ltimes H\right) \ltimes G_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space

Corner symmetries

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} \mathrm{G} &= \quad \mathrm{G}_{\text{kinematical}} \quad \ltimes \mathrm{G}_{\text{dynamical}} \\ &= \big(\mathrm{Diff}(S) \ltimes \mathrm{H}\big) \ltimes \mathrm{G}_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner symmetries

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G &= \quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ &= \big(\text{Diff}(S) \ltimes H\big) \ltimes G_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner terms

Corner symmetries

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G &= \quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ &= \big(\text{Diff}(S) \ltimes H\big) \ltimes G_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner terms

- For any formulation F of gravity, the symplectic potential θ is the sum of

Corner symmetries

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G &= \quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ &= \big(\text{Diff}(S) \ltimes H\big) \ltimes G_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner terms

- For any formulation F of gravity, the symplectic potential θ is the sum of
  - a universal bulk piece, that of canonical ADM, which gives Diff(S)

Corner symmetries

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G &= \quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ &= \big(\text{Diff}(S) \ltimes H\big) \ltimes G_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner terms

- For any formulation F of gravity, the symplectic potential θ is the sum of
  - a universal bulk piece, that of canonical ADM, which gives $\text{Diff}(S)$
  - a corner term, which adds extra charges and components to H

Corner symmetries

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} \mathrm{G} &= \quad \mathrm{G}_{\text{kinematical}} \quad \ltimes \mathrm{G}_{\text{dynamical}} \\ &= \big(\mathrm{Diff}(S) \ltimes \mathrm{H}\big) \ltimes \mathrm{G}_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner terms

- For any formulation F of gravity, the symplectic potential θ is the sum of
  - a universal bulk piece, that of canonical ADM, which gives $\mathrm{Diff}(S)$
  - a corner term, which adds extra charges and components to H

$$\boxed{\theta_{\mathrm{F}} = \theta_{\mathrm{ADM}} + \mathrm{d}\theta_{\mathrm{F/ADM}} + \delta L_{\mathrm{F/ADM}}}$$

Corner symmetries

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G &= \quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ &= \big(\text{Diff}(S) \ltimes H\big) \ltimes G_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner terms

- For any formulation F of gravity, the symplectic potential θ is the sum of
  - a universal bulk piece, that of canonical ADM, which gives $\text{Diff}(S)$
  - a corner term, which adds extra charges and components to H

$$\boxed{\theta_F = \theta_{\text{ADM}} + d\theta_{F/\text{ADM}} + \delta L_{F/\text{ADM}}}$$

- Different formulations have different symmetry groups!

Corner symmetry group of gravity

- The general structure is

$$\begin{aligned} G = &\quad G_{\text{kinematical}} \quad \ltimes G_{\text{dynamical}} \\ = &\big(\text{Diff}(S) \ltimes H\big) \ltimes G_{\text{dynamical}} \end{aligned}$$

- Noether's theorem provides a representation of these symmetries on the phase space
- The subgroup H depends on the formulation of gravity!

Corner terms

- For any formulation F of gravity, the symplectic potential θ is the sum of
  - a universal bulk piece, that of canonical ADM, which gives Diff(S)
  - a corner term, which adds extra charges and components to H

$$\boxed{\theta_F = \theta_{\text{ADM}} + d\theta_{F/\text{ADM}} + \delta L_{F/\text{ADM}}}$$

- Different formulations have different symmetry groups!
- This leads to potentially **inequivalent quantizations**

Example of metric gravity

Corner symmetries

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\mathsf{EH}} = \sqrt{g}\, R$

Corner symmetries

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\text{EH}} = \sqrt{g}\,R$
- Potential

$$
\begin{aligned}
\theta_{\text{EH}} &= \sqrt{q}\,n^\mu \nabla^\nu (\delta g_{\mu\nu} - g_{\mu\nu} g^{\alpha\beta} \delta g_{\alpha\beta}) \\
&= \sqrt{q}\,(K g^{\mu\nu} - K^{\mu\nu}) \delta g_{\mu\nu} + d(\sqrt{q}\,s_\mu \delta n^\mu) - 2\delta(\sqrt{q}\,K) \\
&= \theta_{\text{ADM}} + d\theta_{\text{EH/ADM}} - 2\delta(\sqrt{q}\,K)
\end{aligned}
$$

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\text{EH}} = \sqrt{g}\,R$
- Potential

$$\begin{aligned}\theta_{\text{EH}} &= \sqrt{q}\,n^\mu\nabla^\nu(\delta g_{\mu\nu} - g_{\mu\nu}g^{\alpha\beta}\delta g_{\alpha\beta})\\ &= \sqrt{q}\,(Kg^{\mu\nu} - K^{\mu\nu})\delta g_{\mu\nu} + d(\sqrt{q}\,s_\mu\delta n^\mu) - 2\delta(\sqrt{q}\,K)\\ &= \theta_{\text{ADM}} + d\theta_{\text{EH/ADM}} - 2\delta(\sqrt{q}\,K)\end{aligned}$$

- Boundary Lagrangians (here the GHY term) can carry a corner symplectic structure [Ciambelli, Compère, Freidel, MG, Harlow, Jai-akson, Leigh, Marolf, Pranzetti, Speziale, Wald, Wieland, Wu, . . .]

Corner symmetries

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\text{EH}} = \sqrt{g}\,R$
- Potential

$$
\begin{aligned}
\theta_{\text{EH}} &= \sqrt{q}\,n^{\mu}\nabla^{\nu}(\delta g_{\mu\nu} - g_{\mu\nu}g^{\alpha\beta}\delta g_{\alpha\beta}) \\
&= \sqrt{q}\,(Kg^{\mu\nu} - K^{\mu\nu})\delta g_{\mu\nu} + d(\sqrt{q}\,s_{\mu}\delta n^{\mu}) - 2\delta(\sqrt{q}\,K) \\
&= \theta_{\text{ADM}} + d\theta_{\text{EH/ADM}} - 2\delta(\sqrt{q}\,K)
\end{aligned}
$$

- Boundary Lagrangians (here the GHY term) can carry a corner symplectic structure [Ciambelli, Compère, Freidel, MG, Harlow, Jai-akson, Leigh, Marolf, Pranzetti, Speziale, Wald, Wieland, Wu, . . .]
- Boundary terms do **not** necessarily implement canonical transformations

Corner symmetries

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\text{EH}} = \sqrt{g}\,R$
- Potential

$$\begin{aligned}\theta_{\text{EH}} &= \sqrt{q}\,n^\mu\nabla^\nu(\delta g_{\mu\nu} - g_{\mu\nu}g^{\alpha\beta}\delta g_{\alpha\beta})\\ &= \sqrt{q}\,(Kg^{\mu\nu} - K^{\mu\nu})\delta g_{\mu\nu} + d(\sqrt{q}\,s_\mu\delta n^\mu) - 2\delta(\sqrt{q}\,K)\\ &= \theta_{\text{ADM}} + d\theta_{\text{EH/ADM}} - 2\delta(\sqrt{q}\,K)\end{aligned}$$

- Boundary Lagrangians (here the GHY term) can carry a corner symplectic structure [Ciambelli, Compère, Freidel, MG, Harlow, Jai-akson, Leigh, Marolf, Pranzetti, Speziale, Wald, Wieland, Wu, . . .]
- Boundary terms do **not** necessarily implement canonical transformations
- Here we find that in ADM part of the symmetries are represented trivially

$$\begin{aligned}G^{\text{EH}}_{\text{kinematical}} &= \text{Diff}(S)\ltimes SL(2,\mathbb{R})_\perp\\ G^{\text{ADM}}_{\text{kinematical}} &= \text{Diff}(S)\end{aligned}$$

Corner symmetries

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\text{EH}} = \sqrt{g}\,R$
- Potential

$$\begin{aligned}\theta_{\text{EH}} &= \sqrt{q}\,n^\mu \nabla^\nu(\delta g_{\mu\nu} - g_{\mu\nu} g^{\alpha\beta}\delta g_{\alpha\beta}) \\ &= \sqrt{q}\,(K g^{\mu\nu} - K^{\mu\nu})\delta g_{\mu\nu} + \mathrm{d}(\sqrt{q}\,s_\mu \delta n^\mu) - 2\delta(\sqrt{q}\,K) \\ &= \theta_{\text{ADM}} + \mathrm{d}\theta_{\text{EH/ADM}} - 2\delta(\sqrt{q}\,K)\end{aligned}$$

- Boundary Lagrangians (here the GHY term) can carry a corner symplectic structure [Ciambelli, Compère, Freidel, MG, Harlow, Jai-akson, Leigh, Marolf, Pranzetti, Speziale, Wald, Wieland, Wu, . . .]
- Boundary terms do **not** necessarily implement canonical transformations
- Here we find that in ADM part of the symmetries are represented trivially

$$\begin{aligned}G^{\text{EH}}_{\text{kinematical}} &= \text{Diff}(S) \ltimes \text{SL}(2,\mathbb{R})_\perp \\ G^{\text{ADM}}_{\text{kinematical}} &= \text{Diff}(S)\end{aligned}$$

Going further

Corner symmetries

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\mathsf{EH}} = \sqrt{g}\,R$
- Potential

$$\begin{aligned}\theta_{\mathsf{EH}} &= \sqrt{q}\,n^\mu\nabla^\nu(\delta g_{\mu\nu} - g_{\mu\nu}g^{\alpha\beta}\delta g_{\alpha\beta})\\ &= \sqrt{q}\,(Kg^{\mu\nu} - K^{\mu\nu})\delta g_{\mu\nu} + d(\sqrt{q}\,s_\mu\delta n^\mu) - 2\delta(\sqrt{q}\,K)\\ &= \theta_{\mathsf{ADM}} + d\theta_{\mathsf{EH/ADM}} - 2\delta(\sqrt{q}\,K)\end{aligned}$$

- Boundary Lagrangians (here the GHY term) can carry a corner symplectic structure [Ciambelli, Compère, Freidel, MG, Harlow, Jai-akson, Leigh, Marolf, Pranzetti, Speziale, Wald, Wieland, Wu, . . .]
- Boundary terms do **not** necessarily implement canonical transformations
- Here we find that in ADM part of the symmetries are represented trivially

$$\begin{aligned}G^{\mathsf{EH}}_{\mathsf{kinematical}} &= \mathsf{Diff}(S)\ltimes \mathsf{SL}(2,\mathbb{R})_\perp\\ G^{\mathsf{ADM}}_{\mathsf{kinematical}} &= \mathsf{Diff}(S)\end{aligned}$$

Going further

- If G plays a role in quantizing gravity, what is its largest extension?

Corner symmetries

Example of metric gravity

- Einstein–Hilbert Lagrangian $L_{\text{EH}} = \sqrt{g}\,R$
- Potential

$$\begin{aligned}\theta_{\text{EH}} &= \sqrt{q}\,n^{\mu}\nabla^{\nu}(\delta g_{\mu\nu} - g_{\mu\nu}g^{\alpha\beta}\delta g_{\alpha\beta})\\ &= \sqrt{q}\,(Kg^{\mu\nu} - K^{\mu\nu})\delta g_{\mu\nu} + d(\sqrt{q}\,s_{\mu}\delta n^{\mu}) - 2\delta(\sqrt{q}\,K)\\ &= \theta_{\text{ADM}} + d\theta_{\text{EH/ADM}} - 2\delta(\sqrt{q}\,K)\end{aligned}$$

- Boundary Lagrangians (here the GHY term) can carry a corner symplectic structure [Ciambelli, Compère, Freidel, MG, Harlow, Jai-akson, Leigh, Marolf, Pranzetti, Speziale, Wald, Wieland, Wu, . . .]
- Boundary terms do **not** necessarily implement canonical transformations
- Here we find that in ADM part of the symmetries are represented trivially

$$\begin{aligned}G^{\text{EH}}_{\text{kinematical}} &= \text{Diff}(S)\ltimes \text{SL}(2,\mathbb{R})_{\perp}\\ G^{\text{ADM}}_{\text{kinematical}} &= \text{Diff}(S)\end{aligned}$$

Going further

- If G plays a role in quantizing gravity, what is its largest extension?
- What do different formulations reveal about gravity?

Example of tetrad gravity [Freidel, MG, Pranzetti]

Corner symmetries

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)

Corner symmetries

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)
- The potential differs from that of canonical gravity by a corner term

$$\theta = E \wedge \delta K + d(E \delta n + \gamma \delta e \wedge e)$$

Corner symmetries

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma)E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)
- The potential differs from that of canonical gravity by a corner term

$$\theta = E \wedge \delta K + d(E\delta n + \gamma \delta e \wedge e)$$

- New charges are activated classically, and new quantum numbers at the quantum level

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)
- The potential differs from that of canonical gravity by a corner term

$$\theta = E \wedge \delta K + d(E \delta n + \gamma \delta e \wedge e)$$

- New charges are activated classically, and new quantum numbers at the quantum level
- The symmetry group is

$$G_{\text{kinematical}} = \text{Diff}(S) \ltimes \big(SL(2, \mathbb{C}) \times SL(2, \mathbb{R})_{\parallel}\big)$$

Corner symmetries

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)
- The potential differs from that of canonical gravity by a corner term

$$\theta = E \wedge \delta K + d(E \delta n + \gamma \delta e \wedge e)$$

- New charges are activated classically, and new quantum numbers at the quantum level
- The symmetry group is

$$G_{\text{kinematical}} = \text{Diff}(S) \ltimes \big(SL(2,\mathbb{C}) \times SL(2,\mathbb{R})_{\parallel}\big)$$

- When $\gamma \neq 0$ the metric on S satisfies an $SL(2,\mathbb{R})$ algebra with Casimir $\mathcal{C} = -\big(\gamma\sqrt{q}\big)^2$

Corner symmetries

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)
- The potential differs from that of canonical gravity by a corner term

$$\theta = E \wedge \delta K + d(E \delta n + \gamma \delta e \wedge e)$$

- New charges are activated classically, and new quantum numbers at the quantum level
- The symmetry group is

$$G_{\text{kinematical}} = \text{Diff}(S) \ltimes \big(SL(2,\mathbb{C}) \times SL(2,\mathbb{R})_{\parallel}\big)$$

- When $\gamma \neq 0$ the metric on S satisfies an $SL(2,\mathbb{R})$ algebra with Casimir $\mathcal{C} = -\big(\gamma\sqrt{q}\big)^2$
- This implies that the **area of S is quantized**

$$\sqrt{q}(\sigma) = \gamma^{-1}\, \ell_{\text{Planck}}^2 \sum_i \sqrt{j_i(j_i+1)}\, \delta^{(2)}(\sigma - \sigma_i)$$

Corner symmetries

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)
- The potential differs from that of canonical gravity by a corner term

$$\theta = E \wedge \delta K + d(E\delta n + \gamma \delta e \wedge e)$$

- New charges are activated classically, and new quantum numbers at the quantum level
- The symmetry group is

$$G_{\text{kinematical}} = \text{Diff}(S) \ltimes \big(\text{SL}(2,\mathbb{C}) \times \text{SL}(2,\mathbb{R})_{\parallel}\big)$$

- When $\gamma \neq 0$ the metric on S satisfies an $\text{SL}(2,\mathbb{R})$ algebra with Casimir $\mathcal{C} = -\big(\gamma\sqrt{q}\big)^2$
- This implies that the **area of S is quantized**

$$\sqrt{q}(\sigma) = \gamma^{-1}\,\ell^2_{\text{Planck}} \sum_i \sqrt{j_i(j_i+1)}\,\delta^{(2)}(\sigma - \sigma_i)$$

- **Foundational result of loop quantum gravity** [Ashtekar, Rovelli, Smolin, Lewandowski] derived here in the continuum, without extra inputs

Corner symmetries

Example of tetrad gravity [Freidel, MG, Pranzetti]

- Let us consider a Lagrangian in connection and tetrad variables

$$L = (* + \gamma) E \wedge F \qquad\qquad E = e \wedge e$$

- γ is the Barbero–Immirzi parameter, which multiplies a topological term (like θ-YM)
- The potential differs from that of canonical gravity by a corner term

$$\theta = E \wedge \delta K + d(E\delta n + \gamma \delta e \wedge e)$$

- New charges are activated classically, and new quantum numbers at the quantum level
- The symmetry group is

$$G_{\text{kinematical}} = \text{Diff}(S) \ltimes \big(SL(2,\mathbb{C}) \times SL(2,\mathbb{R})_{\parallel}\big)$$

- When $\gamma \neq 0$ the metric on S satisfies an $SL(2,\mathbb{R})$ algebra with Casimir $\mathcal{C} = -\big(\gamma\sqrt{q}\big)^2$
- This implies that the **area of S is quantized**

$$\sqrt{q}(\sigma) = \gamma^{-1}\,\ell^2_{\text{Planck}} \sum_i \sqrt{j_i(j_i+1)}\,\delta^{(2)}(\sigma - \sigma_i)$$

- **Foundational result of loop quantum gravity** [Ashtekar, Rovelli, Smolin, Lewandowski] derived here in the continuum, without extra inputs
- The free parameter γ is also related to **dual charges**, i.e. potentially measurable [De Paoli, Godazgar, Godazgar, Kol, Speziale, Oblak, Oliveri, Perry, Pope, Porrati, Seraj, . . .]

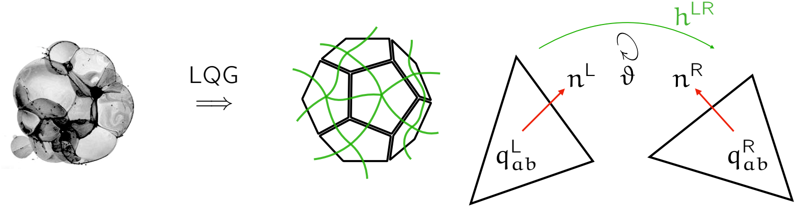
	Corner symmetries				
Formulation of 4d gravity	Diff(S)	SL$(2,\mathbb{R})_\perp$	SL$(2,\mathbb{R})_\parallel$	SU(2)	Boosts
Canonical ADM	✓				
Einstein–Hilbert	✓	✓			
Einstein–Cartan	✓				✓
Einstein–Cartan–γ (LQG)	✓		✓	✓	✓

3d Einstein–Cartan	Diff(S)$\ltimes$Diff(S) or Diff(S)$\ltimes$Vect(S)$_{\text{ab}}$ when $\Lambda = 0$

??? $\longrightarrow$

$\downarrow$

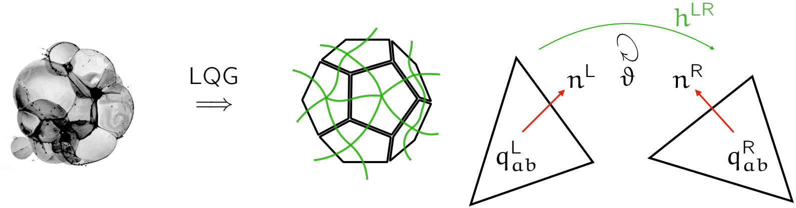
Loop quantum gravity redux



Loop quantum gravity redux

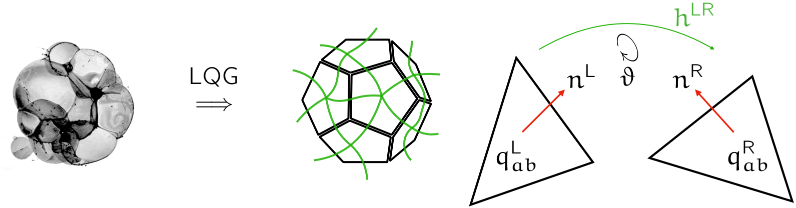
- Based on a particular finite-dimensional truncation and representation of $G_{\text{kinematical}}$

Loop quantum gravity at the corner



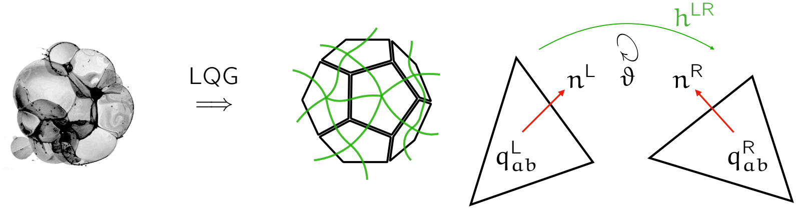
Loop quantum gravity redux

- Based on a particular finite-dimensional truncation and representation of $G_{\text{kinematical}}$
- The basic variables are



Loop quantum gravity redux

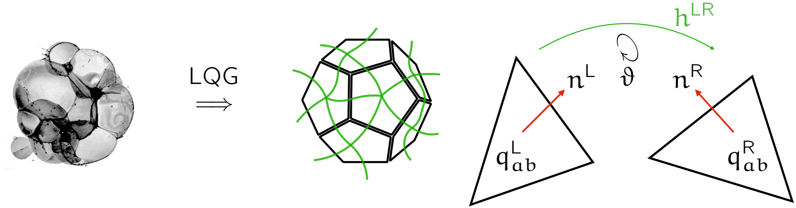
- Based on a particular finite-dimensional truncation and representation of $G_{\text{kinematical}}$
- The basic variables are
  - fluxes (electric fields) encoding the non-commutative boundary metric q_{ab}



Loop quantum gravity redux

- Based on a particular finite-dimensional truncation and representation of $G_{\text{kinematical}}$
- The basic variables are
  - fluxes (electric fields) encoding the non-commutative boundary metric q_{ab}
  - holonomies h encoding the gluing of neighboring boundary data

Loop quantum gravity at the corner



Loop quantum gravity redux

- Based on a particular finite-dimensional truncation and representation of $G_{\text{kinematical}}$
- The basic variables are
  - fluxes (electric fields) encoding the non-commutative boundary metric q_{ab}
  - holonomies h encoding the gluing of neighboring boundary data
- This grounds LQG into the framework of local holography [Bianchi, Dittrich, Freidel, MG, Goeller, Girelli, Han, Livine, Perez, Pranzetti, Riello, Speziale, Tsimiklis, Wieland, . . .]

Lessons

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**
- The least we can do is try to **identify these boundary symmetry groups**

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**
- The least we can do is try to **identify these boundary symmetry groups**
- They contain **formulation-dependent** infos. about classical and quantum gravity

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**
- The least we can do is try to **identify these boundary symmetry groups**
- They contain **formulation-dependent** infos. about classical and quantum gravity

Prospects

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**
- The least we can do is try to **identify these boundary symmetry groups**
- They contain **formulation-dependent** infos. about classical and quantum gravity

Prospects

- Quantize and represent the boundary symmetry groups

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**
- The least we can do is try to **identify these boundary symmetry groups**
- They contain **formulation-dependent** infos. about classical and quantum gravity

Prospects

- Quantize and represent the boundary symmetry groups
- Understand how strongly symmetries constrain the dynamics (charge conservation)

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**
- The least we can do is try to **identify these boundary symmetry groups**
- They contain **formulation-dependent** infos. about classical and quantum gravity

Prospects

- Quantize and represent the boundary symmetry groups
- Understand how strongly symmetries constrain the dynamics (charge conservation)
- Inclusion of matter

Perspectives

Lessons

- In gravity (gauge theory), **physical information is encoded on corners**
- This is **gravity revealing its holographic nature through Noether's theorems**
- The least we can do is try to **identify these boundary symmetry groups**
- They contain **formulation-dependent** infos. about classical and quantum gravity

Prospects

- Quantize and represent the boundary symmetry groups
- Understand how strongly symmetries constrain the dynamics (charge conservation)
- Inclusion of matter

Thanks for your attention!