Title: Local Holography and corner symmetry: A paradigm for quantum gravity

Speakers: Laurent Freidel

Collection: Quantum Gravity Around the Corner

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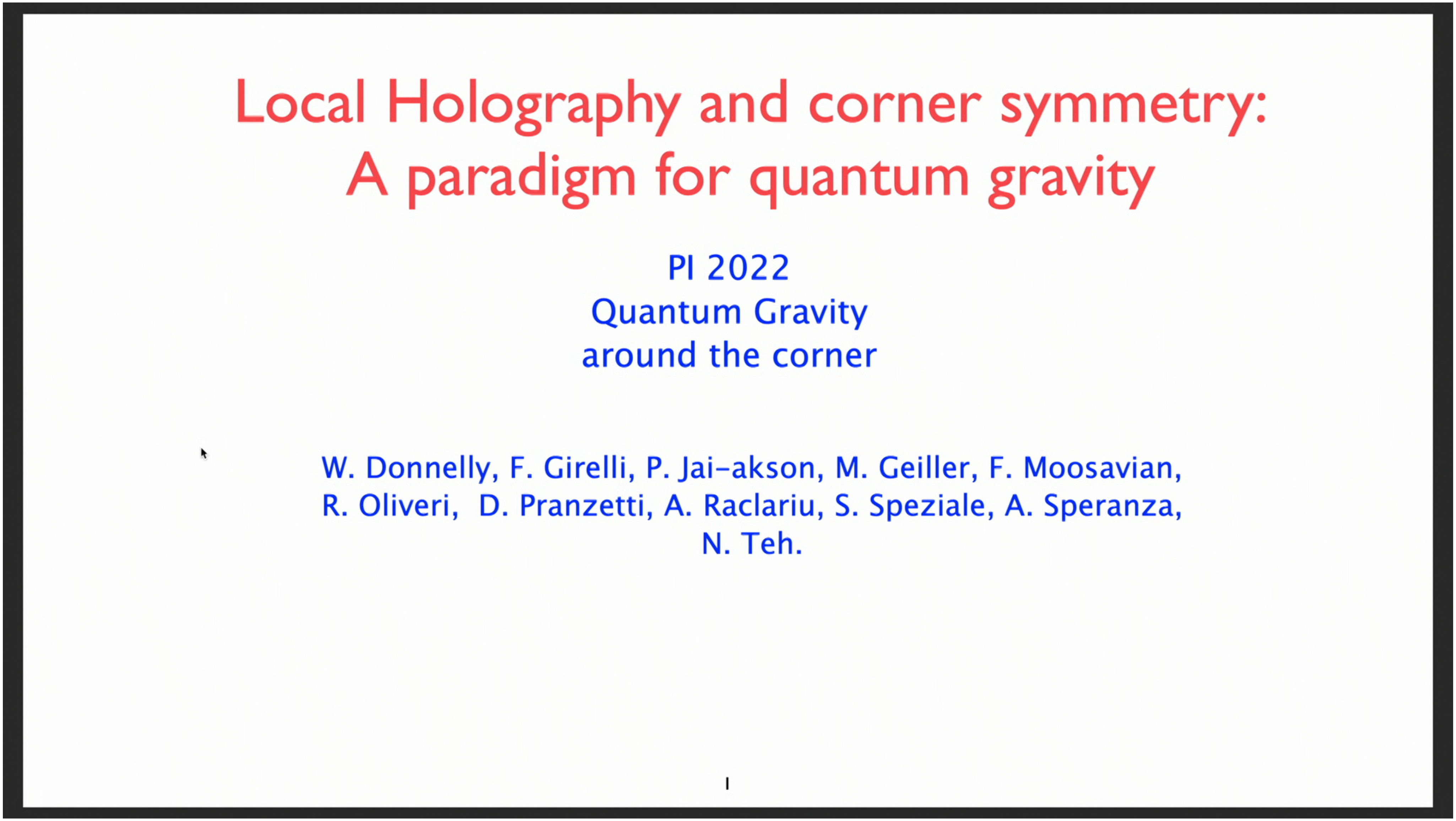
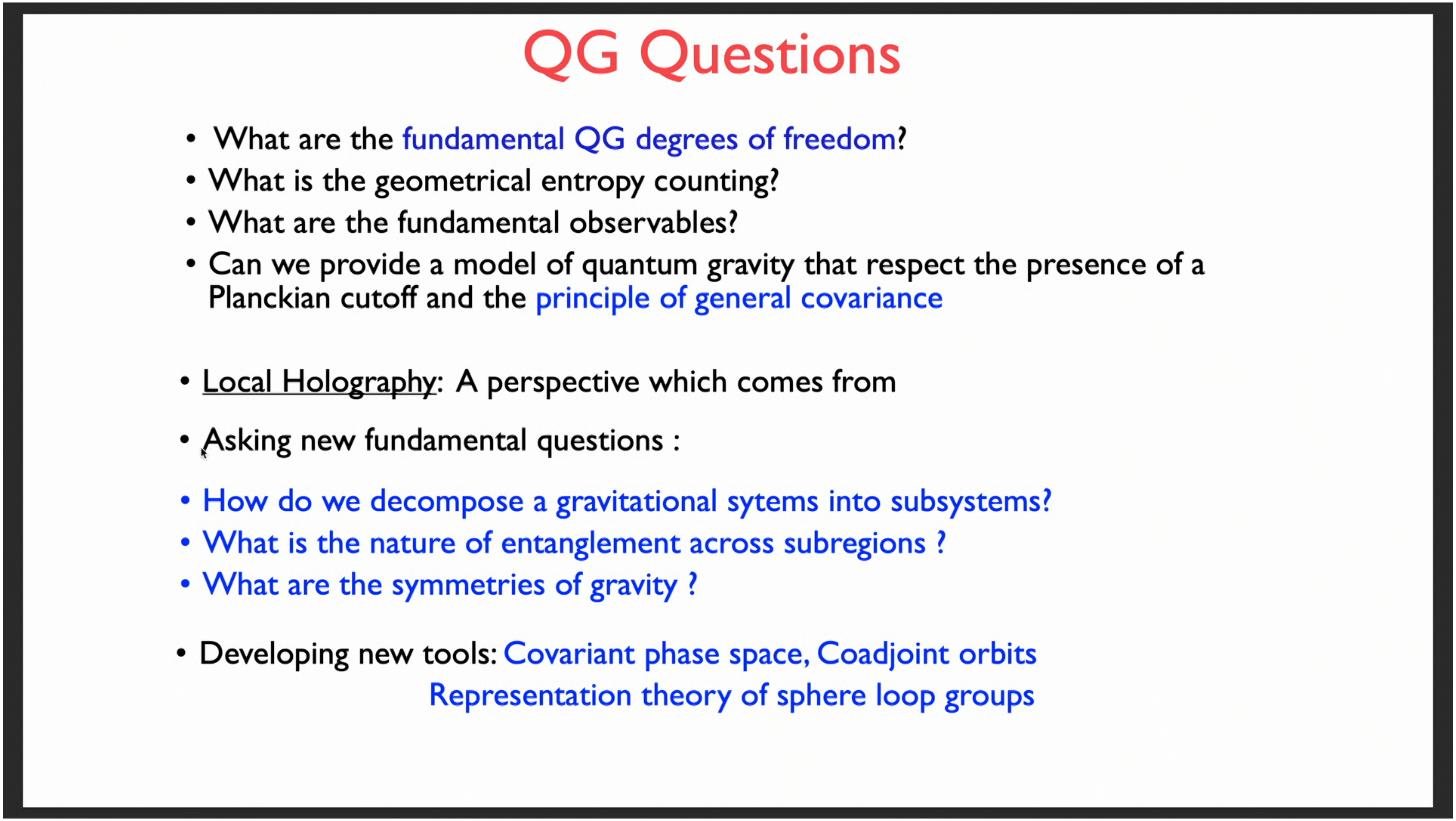
Abstract: In this introductory talk, I will present a new perspective about quantum gravity which is rooted deeply in a renewed understanding of local symmetries in Gravity that appears when we decompose gravitational systems into subsystems.
I will emphasize the central role of the corner symmetry group in capturing all the necessary data needed to glue back seamlessly quantum spacetime regions. I will present how the charge conservation associated with these symmetries encoded the dynamics of null surfaces.
Finally, I will also present how the representation theory of the corner symmetry arises and provides a representation of quantum geometry, and I will show that deformations of this symmetry can be the explanation for a fundamental planckian cut-off.
I will also mention how these symmetry groups reduce to asymptotic symmetry groups and control asymptotic gravitational dynamics when the entangling sphere is moved to infinity. If time permits, I will explain how these symmetries control asymptotic gravitational dynamics. And I will describe how they provide a new picture of the nature of quantum radiation.
Overall, this new paradigm allows to connect semi-classical gravitational physics, S-matrix theory, and non-perturbative quantum gravity techniques.
The talk's goal is to give an overall flavor of how these connections appear from an elementary understanding of symmetries.



Local Holography and corner symmetry: A paradigm for quantum gravity

PI 2022
Quantum Gravity
around the corner

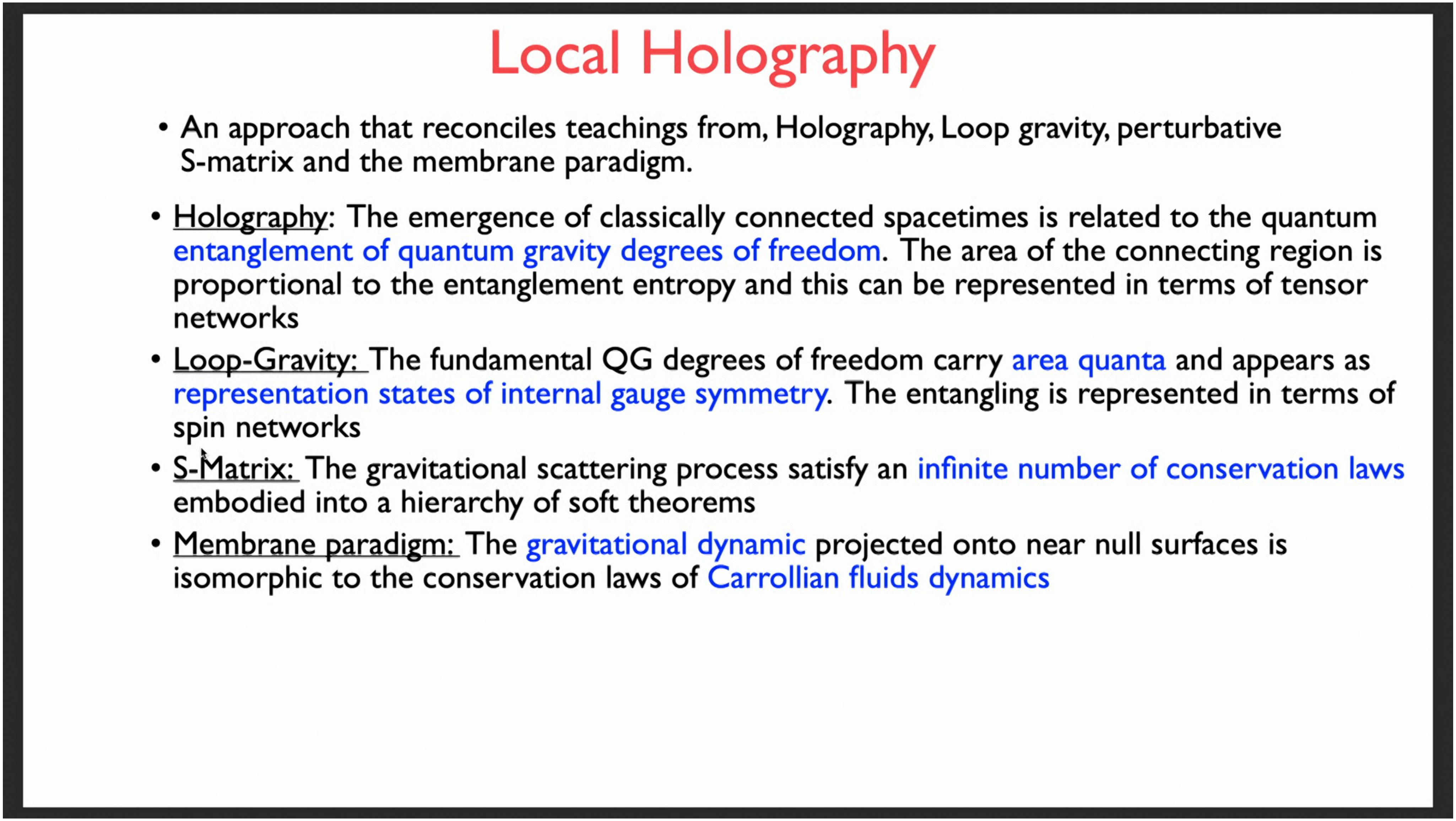
W. Donnelly, F. Girelli, P. Jai-akson, M. Geiller, F. Moosavian,
R. Oliveri, D. Pranzetti, A. Raclariu, S. Speziale, A. Speranza,
N. Teh.



QG Questions

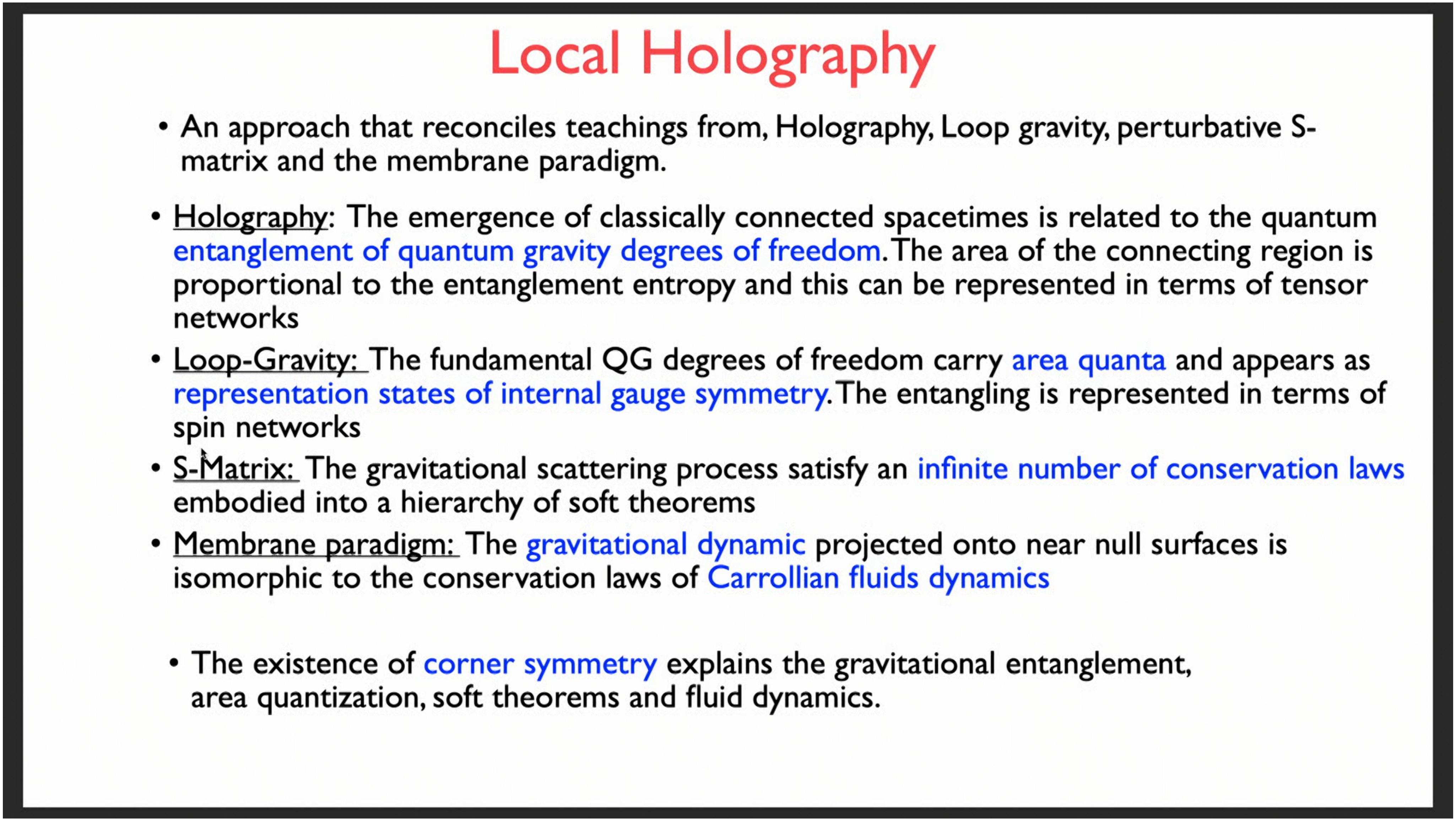
- What are the fundamental QG degrees of freedom?
- What is the geometrical entropy counting?
- What are the fundamental observables?
- Can we provide a model of quantum gravity that respect the presence of a Planckian cutoff and the principle of general covariance

- Local Holography: A perspective which comes from
- Asking new fundamental questions :
- How do we decompose a gravitational sytems into subsystems?
- What is the nature of entanglement across subregions ?
- What are the symmetries of gravity ?
- Developing new tools: Covariant phase space, Coadjoint orbits
  Representation theory of sphere loop groups



Local Holography

- An approach that reconciles teachings from, Holography, Loop gravity, perturbative S-matrix and the membrane paradigm.
- Holography: The emergence of classically connected spacetimes is related to the quantum entanglement of quantum gravity degrees of freedom. The area of the connecting region is proportional to the entanglement entropy and this can be represented in terms of tensor networks
- Loop-Gravity: The fundamental QG degrees of freedom carry area quanta and appears as representation states of internal gauge symmetry. The entangling is represented in terms of spin networks
- S-Matrix: The gravitational scattering process satisfy an infinite number of conservation laws embodied into a hierarchy of soft theorems
- Membrane paradigm: The gravitational dynamic projected onto near null surfaces is isomorphic to the conservation laws of Carrollian fluids dynamics



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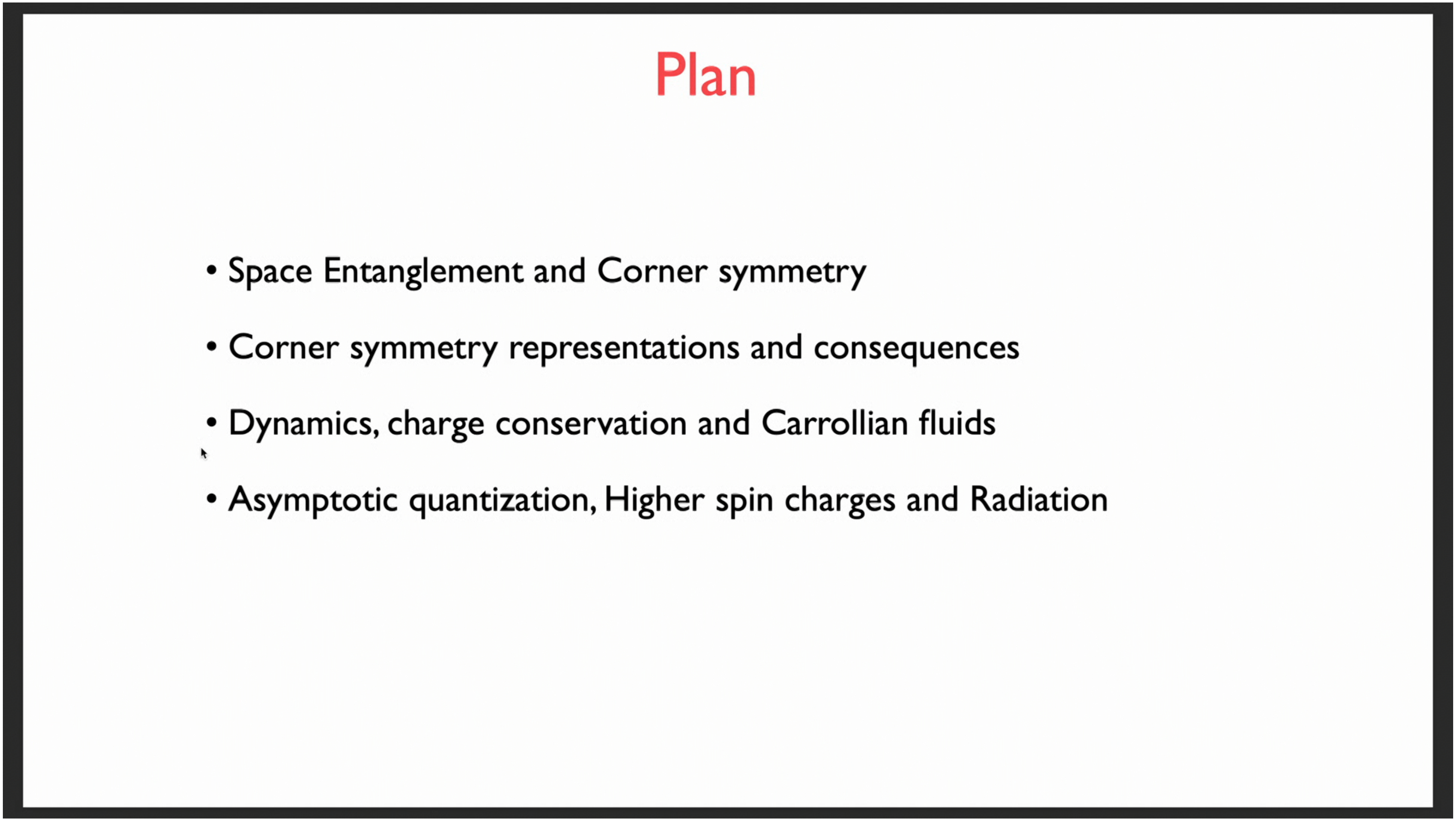
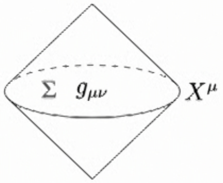
- The existence of corner symmetry explains the gravitational entanglement, area quantization, soft theorems and fluid dynamics.



Plan

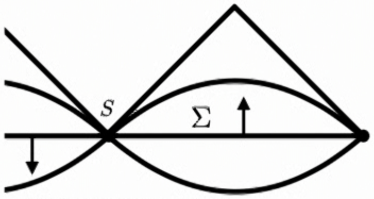
- Space Entanglement and Corner symmetry
- Corner symmetry representations and consequences
- Dynamics, charge conservation and Carrollian fluids
- Asymptotic quantization, Higher spin charges and Radiation

Gauge symmetry resolves entanglement



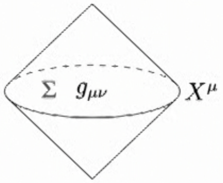
- The basic set-up is to decompose a slice of spacetime into a collection of regions and understand what data is necessary to glue them back.

$$\Sigma = \cup_i \Sigma_i$$



- Quantum states are fundamentally entangled across the boundary S of two subregions: What is the nature of this entanglement ?

Gauge symmetry resolves entanglement



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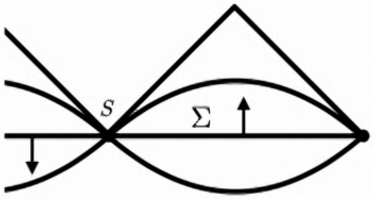


- Quantum states are fundamentally entangled across the boundary S of two subregions: What is the nature of this entanglement ?

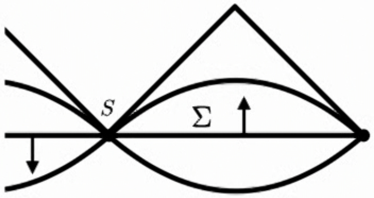
- If there exists a symmetry $Q = Q_L + Q_R$ whose action vanishes on the state $|\Psi\rangle \in \mathscr{H}_{\Sigma_L \cup \Sigma_R}$ We can use it to decompose the state into its symmetry resolved components

$$|\Psi\rangle = \sum_q |\Psi(q)\rangle \quad Q_L|\Psi(q)\rangle = q|\Psi(q)\rangle$$

- This lowers entanglement. example: vaccua states and boost symmetry

Unruh decomposition $|0\rangle = \sum_n e^{-\pi n}|0,n\rangle$ where $|0,n\rangle = |n\rangle \otimes |n^*\rangle$ is pure and n is the boost weigh

Gauge symmetry resolves entanglement



- In gauge theory and gravity there exists an infinite set of symmetry charges are supported on codimension 2 corners.
- These charges form the corner symmetry algebra $\mathfrak{g}_S$

- The gauge principle implies that the action of the total charge $Q = Q_L + Q_R$ vanishes on physical states even if the individual action of $Q_{L/R}$ doesn't.

$$|\Psi\rangle = \sum_{R \in \mathrm{irrep} C_R(\mathfrak{g}_S)} |\Psi(R)\rangle \qquad Q_L|\Psi(R)\rangle = -Q_R|\Psi(R)\rangle$$

- The Hilbert space doesn't factorizes. Instead states have to be decomposed in terms of unitary representations of the corner symmetry algebra

$$\mathscr{H} = \oplus_R \mathscr{H}_L(R) \boxtimes_{G_S} \mathscr{H}_R(R)$$

Donnelly, F '16

- What algebra? For QCD $\mathfrak{g}_S = \mathfrak{g}^S$ is a loop group.
- For gravity it is expression of local diffeo on the sphere and local boost symmetry on S

Noether theorems for local symmetry

- Global symmetries are associated with currents integrated on codimension one slices Σ

$$Q_\xi(\Sigma) = \int_\Sigma J_\xi$$

- For **local symmetries** the Noether current is trivially conserved: This means that there is a Constraints such that $d(J_\xi - C_\xi) = 0$, which implies that $Q(\Sigma) \hat{=} 0$ if $\partial\Sigma = 0$

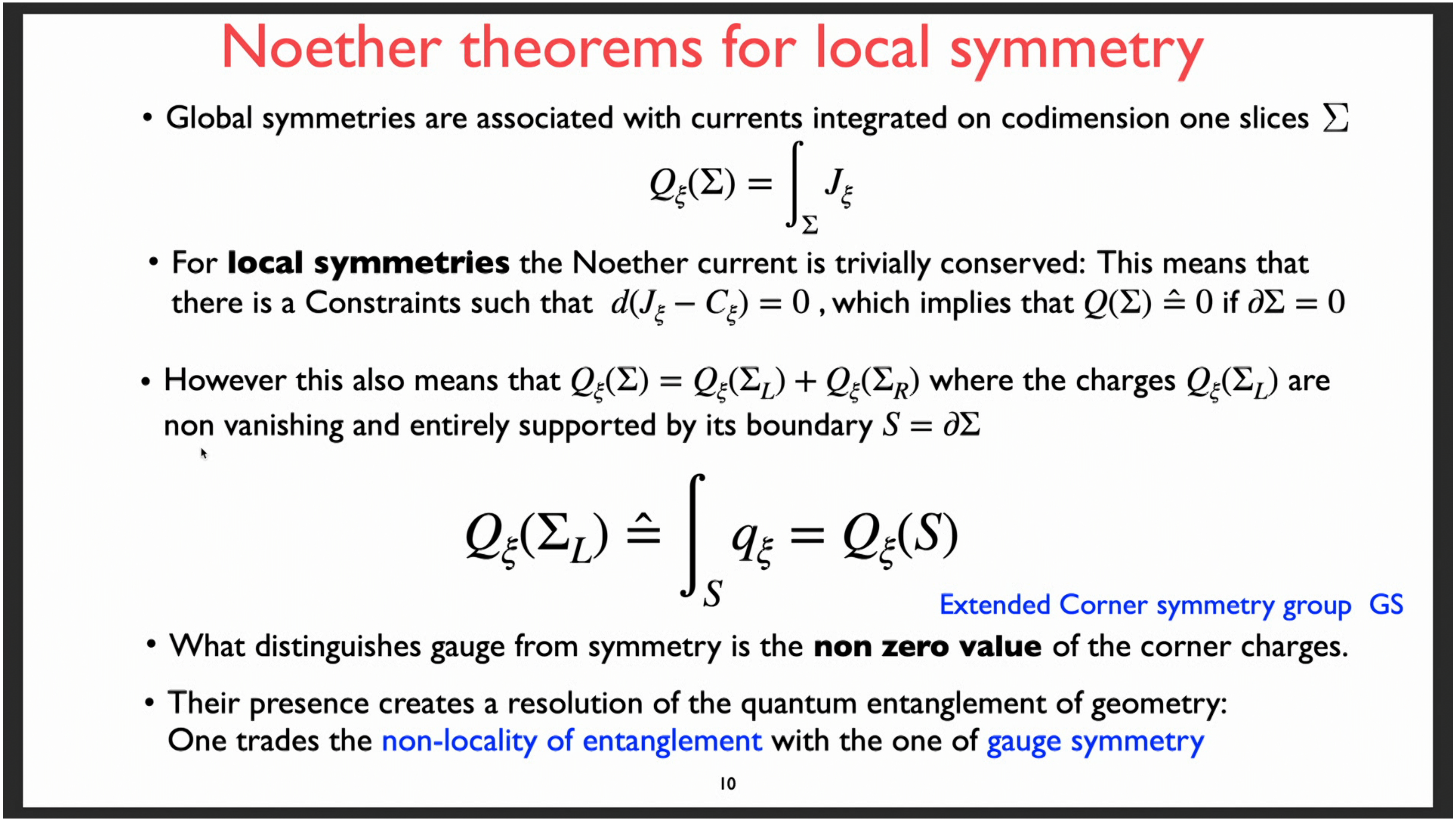
- However this also means that $Q_\xi(\Sigma) = Q_\xi(\Sigma_L) + Q_\xi(\Sigma_R)$ where the charges $Q_\xi(\Sigma_L)$ are non vanishing and entirely supported by its boundary $S = \partial\Sigma$

$$Q_\xi(\Sigma_L) = \int_{\Sigma_L} C_\xi + \int_S q_\xi$$

$$\boxed{C_\xi \hat{=} 0}$$

Constraints

Charge aspect



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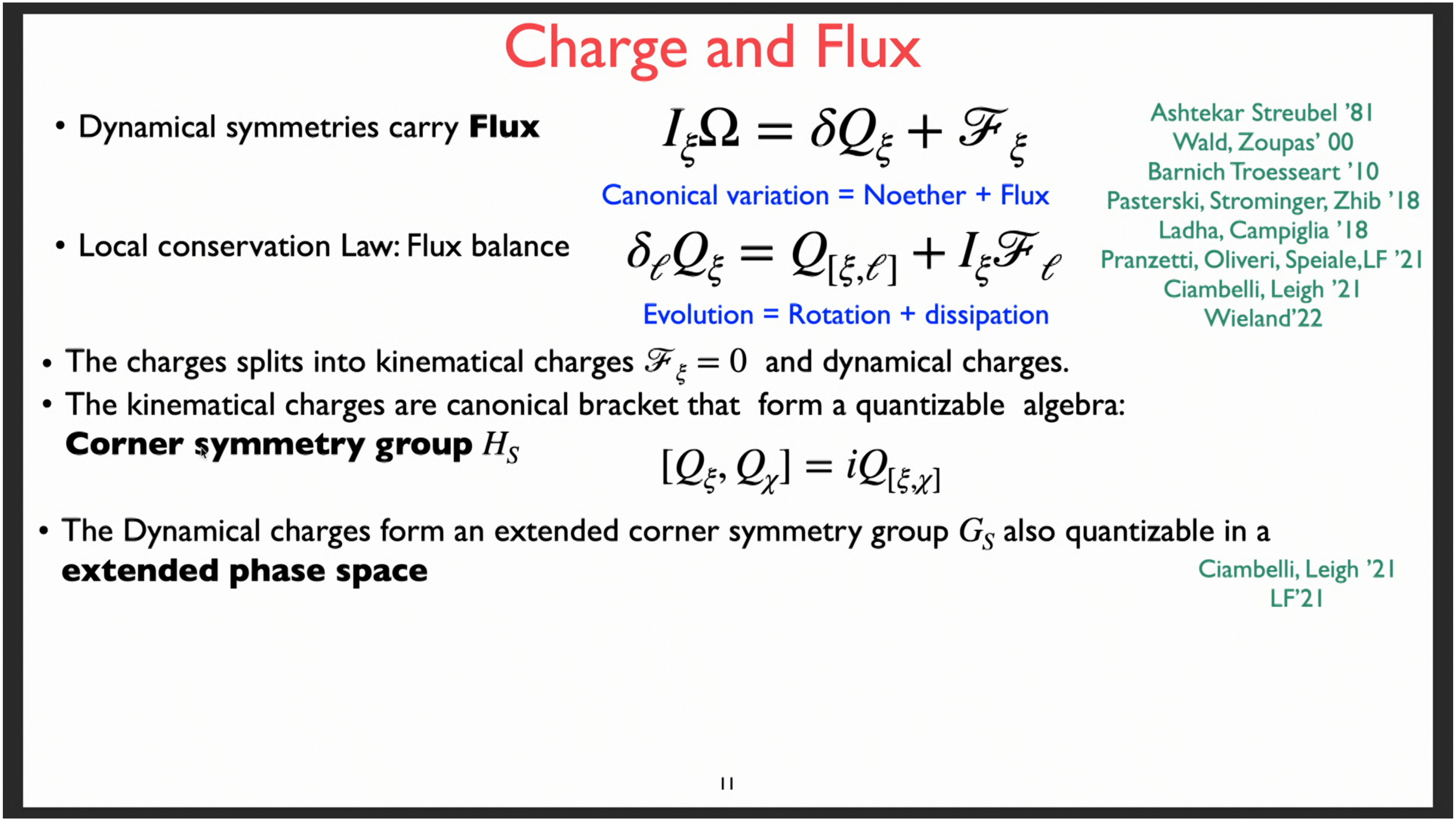
$$Q_\xi(\Sigma_L) \hat{=} \int_S q_\xi = Q_\xi(S)$$

Extended Corner symmetry group GS

- What distinguishes gauge from symmetry is the **non zero value** of the corner charges.

- Their presence creates a resolution of the quantum entanglement of geometry: One trades the non-locality of entanglement with the one of gauge symmetry



Charge and Flux

- Dynamical symmetries carry **Flux**

$$I_\xi \Omega = \delta Q_\xi + \mathscr{F}_\xi$$

Canonical variation = Noether + Flux

- Local conservation Law: Flux balance

$$\delta_\ell Q_\xi = Q_{[\xi,\ell]} + I_\xi \mathscr{F}_\ell$$

Evolution = Rotation + dissipation

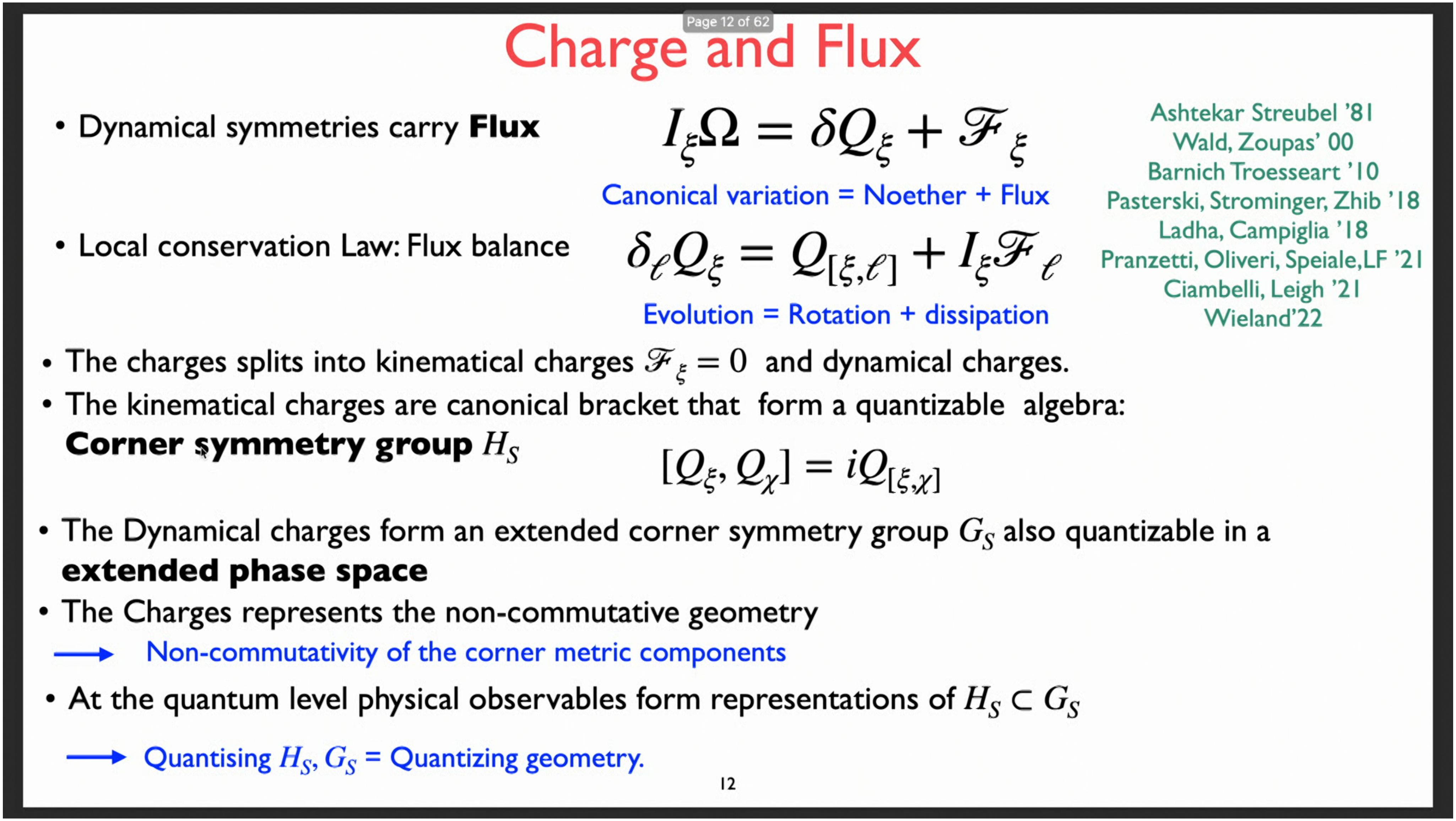
Ashtekar Streubel '81
Wald, Zoupas' 00
Barnich Troesseart '10
Pasterski, Strominger, Zhib '18
Ladha, Campiglia '18
Pranzetti, Oliveri, Speiale,LF '21
Ciambelli, Leigh '21
Wieland'22

- The charges splits into kinematical charges $\mathscr{F}_\xi = 0$ and dynamical charges.
- The kinematical charges are canonical bracket that form a quantizable algebra: **Corner symmetry group** H_S

$$[Q_\xi, Q_\chi] = iQ_{[\xi,\chi]}$$

- The Dynamical charges form an extended corner symmetry group G_S also quantizable in a **extended phase space**

Ciambelli, Leigh '21
LF'21



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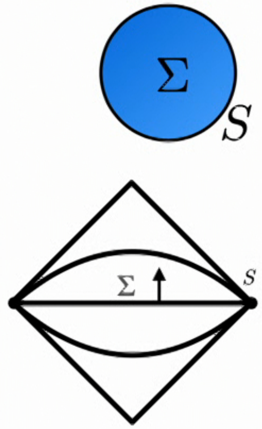
- The Dynamical charges form an extended corner symmetry group G_S also quantizable in a **extended phase space**
- The Charges represents the non-commutative geometry

⟶ Non-commutativity of the corner metric components

- At the quantum level physical observables form representations of $H_S \subset G_S$

⟶ Quantising H_S, G_S = Quantizing geometry.

Symmetries and Gravity



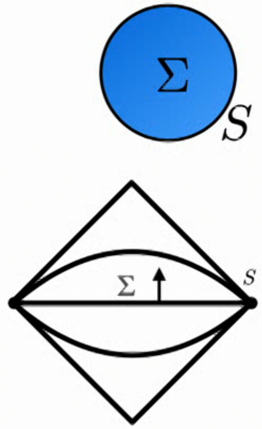
- Given a region R with slice Σ the symmetry charges are supported on codimension 2 corners S= entangling sphere
- The extended corner symmetry group G_S is the subgroup of Diff(M) which and possesses non zero Noether charges in the presence of S, its with kinematical subgroup $H_S \subset G_S$ preserves the region R.
- In <u>metric</u> gravity

$$\boxed{G_S = (\mathrm{Diff}(S) \ltimes \mathrm{SL}(2,\mathbb{R})^S) \ltimes \mathbb{R}^{2\bar{S}}}$$

Group = Kinematical + dynamical

W. Donnelly, L.F 2016
L.F, Leigh, Ciambelli' 21

Symmetries and Gravity



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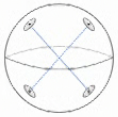
W. Donnelly, L.F 2016
L.F, Leigh, Ciambelli' 21

- Double Universality of G_S for metric gravity!
  -Same group for infinitesimal diamond or very large ones
  -Same group for Einstein gravity or any other higher derivative formulation of gravity no matter how many extra derivative

Wald, Speranza'17

- What changes is either the choice of representation or the canonical representation of the symmetry generators

Extended corner symmetry group



- In metric gravity the group is $G_S = \left(\mathrm{Diff}(S) \ltimes \mathrm{SL}(2,\mathbb{R})^S\right) \ltimes \mathbb{R}^{2S}$
- Given a surface S embedded in space time the tangent bundle can be decomposed in tangential components with coordinates σ^A and normal component with coordinates $x^i = (t, r)$: $S = \{x^i = 0\}$

- The extended corner symmetry algebra is generated by vector fields

$$\xi = T^i\partial_i + Y^A\partial_A + W_i{}^j(x^i\partial_j)$$

super-translation

super-Lorentz diff(S)

super-boost Weyl

- Metric

$$\mathrm{d}s^2 = h_{ij}\mathrm{d}x^i\mathrm{d}x^j + q_{AB}(\mathrm{d}\sigma^A - V_i^A\mathrm{d}x^i)(\mathrm{d}\sigma^B - V_j^B\mathrm{d}x^j)$$

normal metric

tangential metric

Normal lapse

- Canonical diffeo aspect

$$P_A = q_{AB}(\partial_0 V_1^B - \partial_1 V_0^B + [V_0, V_1]^B_{\mathrm{Lie}})$$

Twist1-form

Extended corner symmetry group

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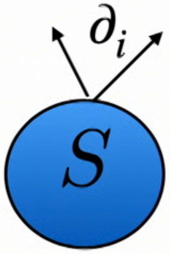

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normal metric

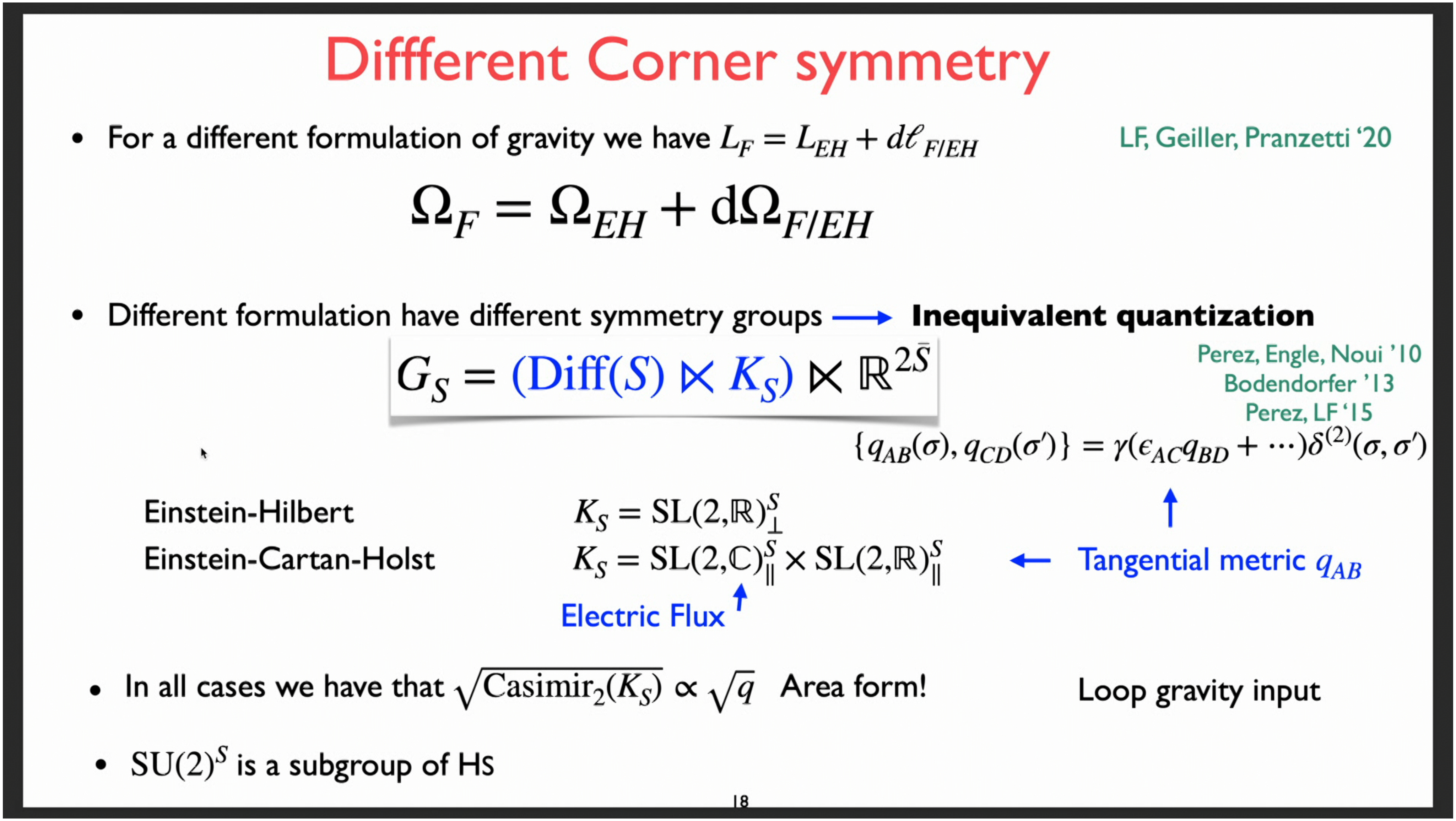
tangential metric

Normal lapse

- Canonical Boost aspect

$$\boxed{N_j{}^i = \epsilon_{jk}h^{ki}}$$

normal metric



Diffferent Corner symmetry

- For a different formulation of gravity we have $L_F = L_{EH} + d\ell_{F/EH}$

LF, Geiller, Pranzetti '20

$$\Omega_F = \Omega_{EH} + \mathrm{d}\Omega_{F/EH}$$

- Different formulation have different symmetry groups ⟶ **Inequivalent quantization**

$$\boxed{G_S = (\mathrm{Diff}(S) \ltimes K_S) \ltimes \mathbb{R}^{2\bar{S}}}$$

Perez, Engle, Noui '10
Bodendorfer '13
Perez, LF '15

$$\{q_{AB}(\sigma), q_{CD}(\sigma')\} = \gamma(\epsilon_{AC}q_{BD} + \cdots)\delta^{(2)}(\sigma,\sigma')$$

↑

Einstein-Hilbert $K_S = \mathrm{SL}(2,\mathbb{R})^S_\perp$

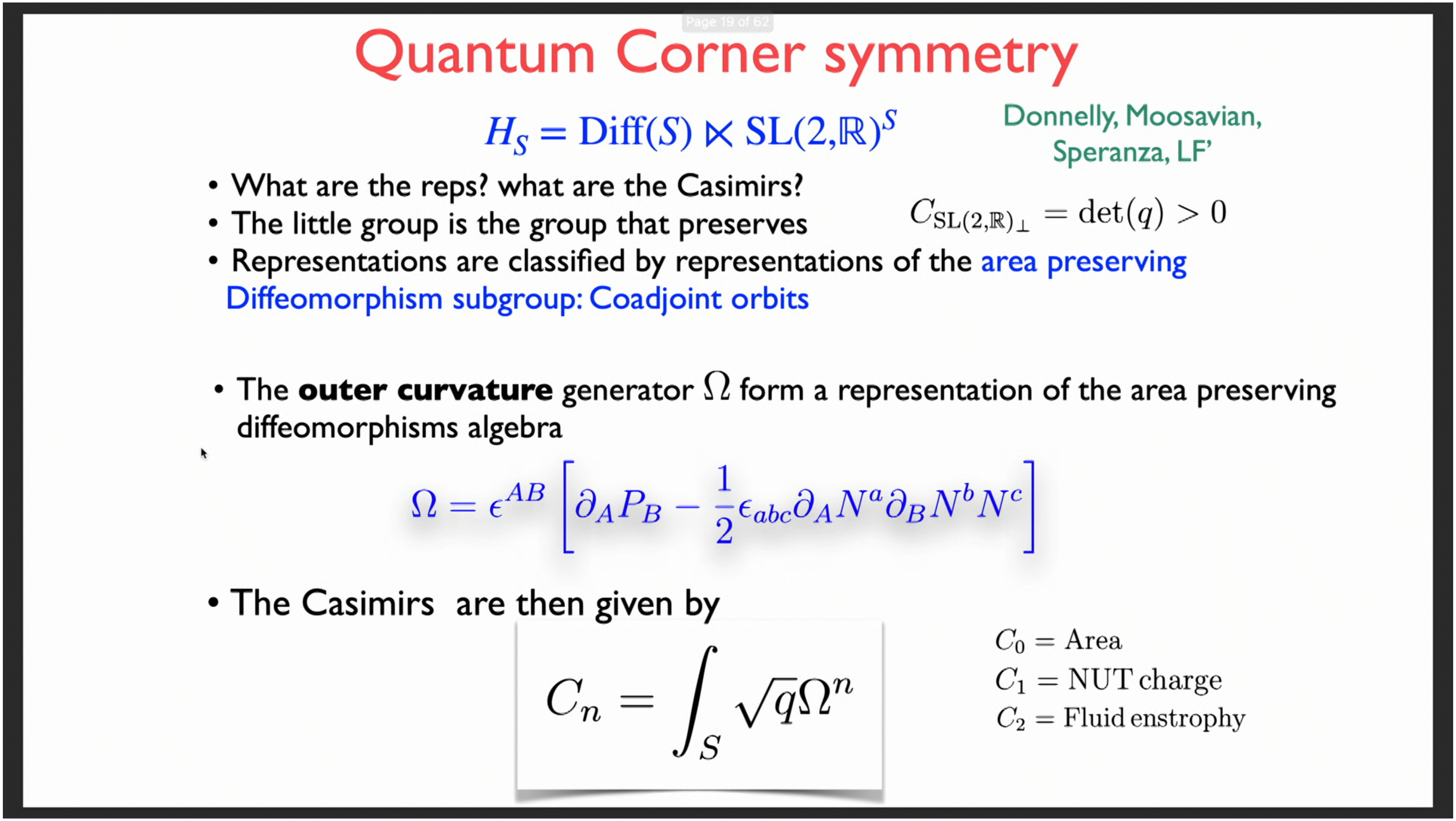
Einstein-Cartan-Holst $K_S = \mathrm{SL}(2,\mathbb{C})^S_\parallel \times \mathrm{SL}(2,\mathbb{R})^S_\parallel$ ← Tangential metric q_{AB}

Electric Flux ↑

- In all cases we have that $\sqrt{\mathrm{Casimir}_2(K_S)} \propto \sqrt{q}$ Area form!

Loop gravity input

- $\mathrm{SU}(2)^S$ is a subgroup of Hs



Quantum Corner symmetry

$$H_S = \mathrm{Diff}(S) \ltimes \mathrm{SL}(2,\mathbb{R})^S$$

Donnelly, Moosavian, Speranza, LF'

- What are the reps? what are the Casimirs?
- The little group is the group that preserves

$$C_{\mathrm{SL}(2,\mathbb{R})_\perp} = \det(q) > 0$$

- Representations are classified by representations of the area preserving Diffeomorphism subgroup: Coadjoint orbits

- The **outer curvature** generator Ω form a representation of the area preserving diffeomorphisms algebra

$$\Omega = \epsilon^{AB}\left[\partial_A P_B - \frac{1}{2}\epsilon_{abc}\partial_A N^a \partial_B N^b N^c\right]$$

- The Casimirs are then given by

$$\boxed{C_n = \int_S \sqrt{q}\,\Omega^n}$$

$C_0 =$ Area

$C_1 =$ NUT charge

$C_2 =$ Fluid enstrophy

Quantum fluid

H_S is isomorphic to the symmetry groups of 2d hydrodynamics

W. Donnelly, A. Speranza, F.M
Moosavian, L.F 2020

- Analogy: the area density $\sqrt{q}$ plays the role of the fluid density ρ
  The outer curvature Ω plays the role of the fluid vorticity w
- The quantum representations are classified by a choice of area and vorticity densities (ρ, w) on S.
- (ρ, w) can be related to labels of the coadjoint orbits (hence representation) of the `fluid group' H_S

Arnold'66; Marsden, Ratiu'95
Khesin'17

- Classical fluid corresponds to a choice of density density measure $\rho > 0$ which is absolutely continuous with respect to the lebesgue measure
- Quantum fluid corresponds to a choice where both ρ and w are counting measures.
  This gives a constituent picture to the fluid

Quantum fluid

W. Donnelly, A. Speranza, F.M
Moosavian, L.F 2020

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Arnold; Marsden, Ratiu,

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- This provides a **constituent picture** where

Fluid molecularization = Area constituent
Vortex quantization = Momenta quantization

M. Geiller, D. Pranzetti, L.F 2021

$$\rho = \sum_i \rho_i \delta^{(2)}(\sigma, \sigma_i)$$

- Each constituent carries a density, weight and spin (ρ_i, Δ_i, s_i)

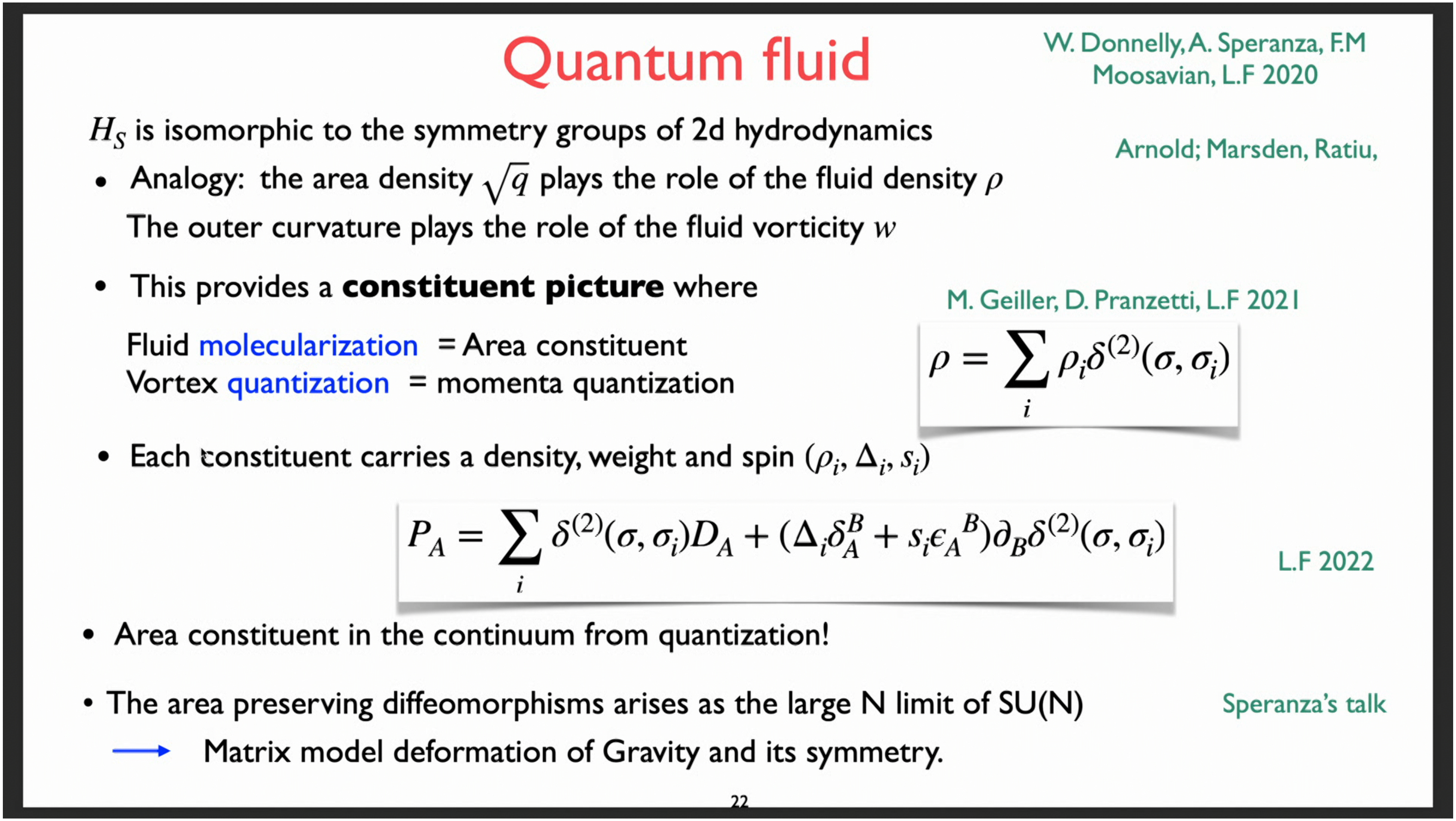
$$P_A = \sum_i \delta^{(2)}(\sigma, \sigma_i) D_A + (\Delta_i \delta_A^B + s_i \epsilon_A{}^B) \partial_B \delta^{(2)}(\sigma, \sigma_i)$$

L.F 2022

- Area constituent in the continuum from quantization!

- Einstein Cartan gravity with an Immirzi parameter implies that $\rho_i = \gamma\sqrt{j_i(j_i+1)}$.
  Area gap in the continuum!

Wieland '19



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L.F 2022

- Area constituent in the continuum from quantization!

- The area preserving diffeomorphisms arises as the large N limit of SU(N)

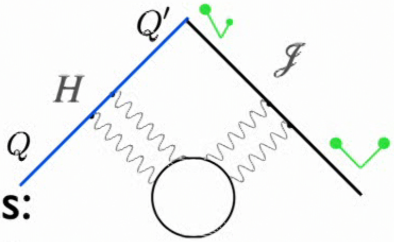
  → Matrix model deformation of Gravity and its symmetry.

Speranza's talk

Dynamics along null surfaces

- In recent years there has been a tremendous effort and renewed understanding using symmetries of gravitational dynamics and Flux along null horizons including null infinity

Ashtekar, Adami, Barnich, Ciambelli, Compere, Chandrasekaran, Donnay, Flanagan, Freidel, Grumiller, Hopfmueller, Gobadazar, Marteau, Oliveri, Petropoulos, Perry, Ruzziconi, Sheikh-Jabbari, Speranza, Speziale, Troesseart, Zwikel, Wieland,…



→ Two main results for finite and asymptotic null surfaces outside caustics:

- The Einstein dynamics along null surfaces is encoded in the evolution Equation of a Carrolllian fluid: $c \to 0$, ultra-local limit of a relativistic fluid.
- This dynamics can be understood as the conservation of charges for a universal symmetry group called BMSW naturally derived from Gs

- The Gravitational dynamics projected on $\mathscr{N}$ can be recast as a set of Null conservation Laws $D_b T_a{}^b = 0$

Carrollian connection

Carrollian energy-momentum tensor

Donnay, Marteau '19
LF, Hopfmueller,'19; Sheikh-Jabbari'20
Speranza, Flanagan, Chandrasekaran 21

Symmetry on null surfaces

- Local gravitational symmetries are attached to codimension 2 corner: In metric gravity this group is the extended corner symmetry group (Universal)

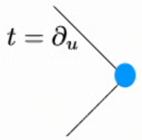
$$G_S = \left(\mathrm{Diff}(S) \ltimes \mathrm{SL}(2,\mathbb{R})^S\right) \ltimes \mathbb{R}^{2S}$$

- When we study Horizon, asymptotic infinity or the nature of quantum radiation one focuses our attention onto a specific null surface. In that case the subgroup preserving the preserving the null structure (Thermal Carrollian structure) is

$$\mathrm{BMSW} = (\mathrm{Diff}(S) \ltimes \mathrm{Weyl}) \ltimes \mathbb{R}^S$$

Barnich-Trossaert'10,
Chandrasekar, Flanagan, Prabhu'18
LF, Oliveri, Pranzetti Speziale '21

$$\boxed{\xi = T\partial_u + Y^A\partial_A + W(u\partial_u - r\partial_r)}$$



- At infinity, same group, conservation law are associated with GBMS

$$W = \frac{1}{2}D_AY^A$$

Barnich Troesseart '11 Campiglia, Ladha '16
Compere, Fiorucci, Ruzziconi'18

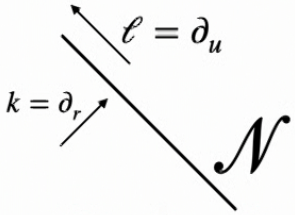
Carrollian Fluid

Levy-Leblond, Perry

A Carrollian Fluid is defined as the ultra-local limit $c \to 0$ of a relativistic fluid.

Donnay, Marteau,
Ciambelli, Leigh, Petropoulos

A Carrollian structure (p, ℓ^a, q_{ab}) on a surface $\mathcal{N}$ is a bundle structure $p : (\mathcal{N}, \ell) \to (S, q_S)$ where q is a metric on S and ℓ is a vector in the kernel of dp the pull-back $q = p^*(q_S)$ defines a null metric on $\mathcal{N}$



An Ehresman connection on $\mathcal{N}$ is a form k dual to ℓ, $\ell^a k_a = 1$

Mars, Senovilla

The embedding of $\mathcal{N}$ in M determines a rigged connection D_a preserving (ℓ, q)

D_a is characterised by a choice of twist form $\omega_a = k_b D_a \ell^b$ and choice of shear $\bar{\theta}_{ab} = q_a{}^{\alpha} q_b{}^{\beta} D_{\alpha} k_{\beta}$

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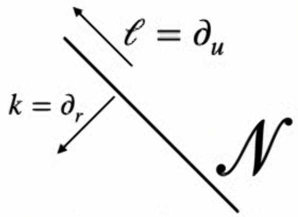

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There is an energy-momentum tensor $$T_a{}^b = -k_a(E\ell^b + J^b) + \pi_a \ell^b + (\tau_a{}^b + P q_a{}^b)$$

- The Gravitational dynamics $G_{\ell a} = 0$ projected on $\mathcal{N}$ can be recast as a set of Null conservation Laws $D_b T_a{}^b = 0$ where

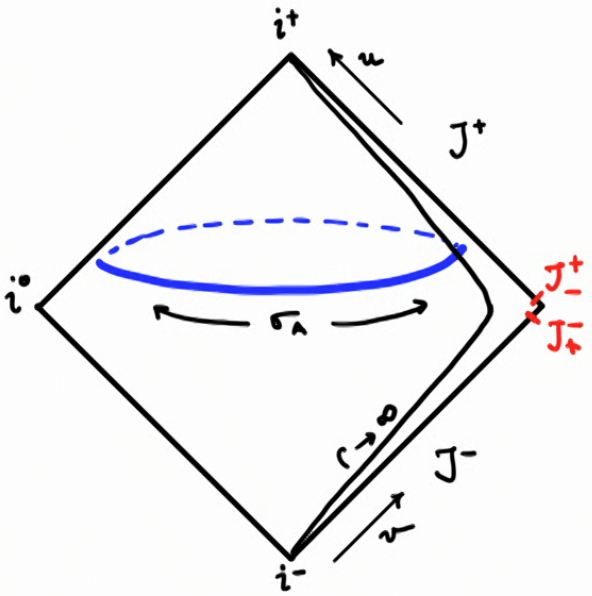
$$\begin{cases} J^a = 0 \\ \omega_a = \pi_a - \left(P + \frac{1}{2}E\right) k_a \\ \tau_{ab} = \mathcal{L}_\ell q_{ab} \end{cases}$$

LF, Hopfmueller '18, Sheikh-Jabbari '20
Speranza, Flanagan, Chandrasekaran '21

- These laws are the conservation of a subset BMSW charges along $\mathcal{N}$
- The conservation of Weyl Charges provides the missing Einsteins equation $G_{\ell k}$

LF Jai-akson '22

Asymptotic infinity



- In flat space asymptotic the corner is placed at ι_0
- The asymptotic symmetry is $\mathrm{GBMS} = \mathrm{Diff}(S) \ltimes R^S_{-1}$
- The asymptotic dynamic is Carrolllian

Ruzziconi, Fiorucci'19
Petropoulos, Ciambelli, 22
Donnay, Ruzziconi' 22

- In pure gravity we can assume that the corner symmetry charges vanish at $\iota_\pm$. If Matter is present we assume that $Q_\xi(\iota_\pm) = Q_\xi^{\mathrm{Hard}}(\rho_{\mathrm{matter}})$

- This assumption and the conservation law implies that the charges can be written in terms of the radiative data at $\mathcal{J}$

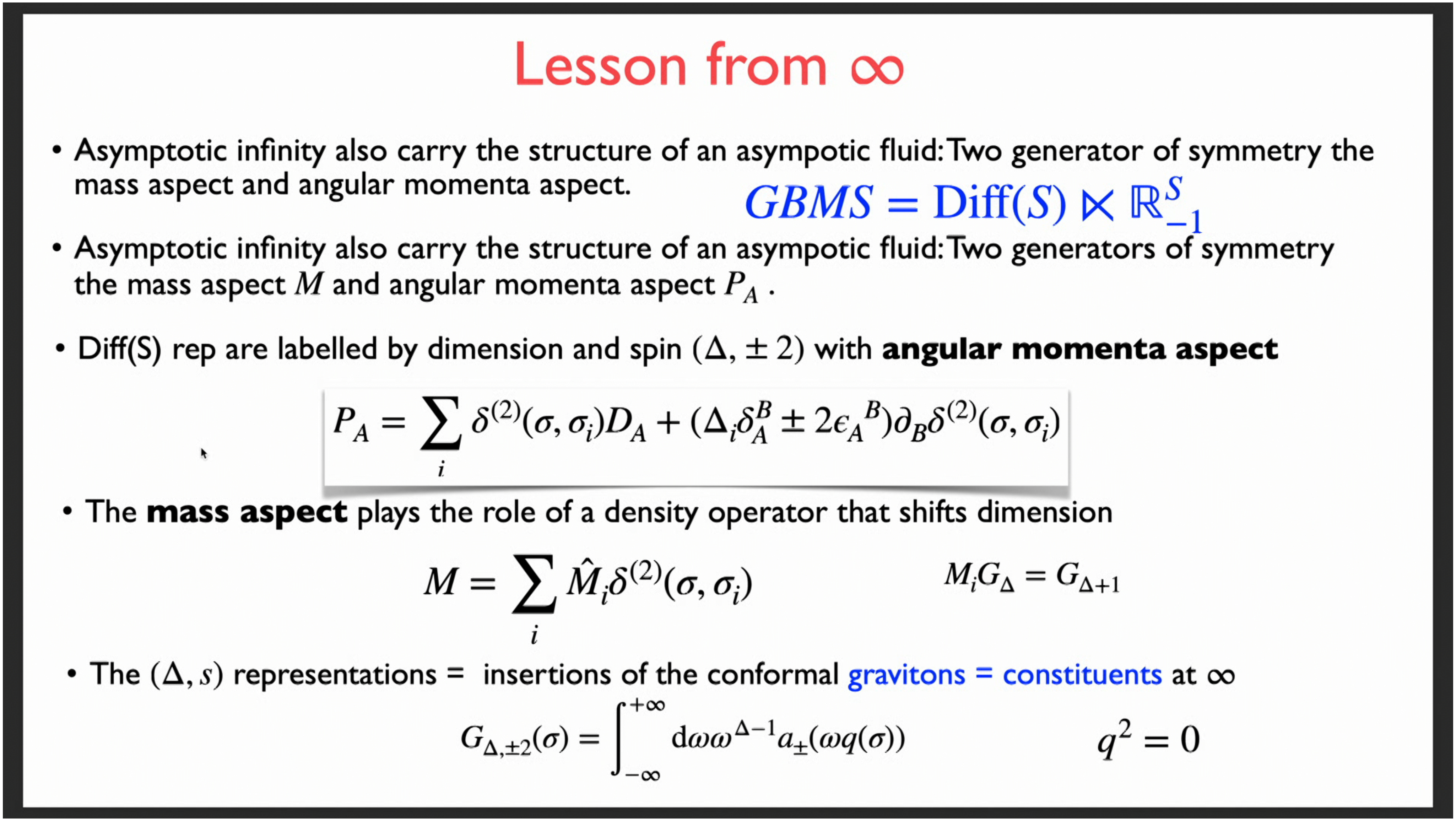
$$Q_\xi(\iota_0^\pm) = \int_{\mathcal{J}} \xi^a q_a(C_{AB}) \longrightarrow \text{Quantum operator on } \mathscr{F}$$

$$[C_{AB}(u,z), \dot{C}^{CD}(u',z')] = i\kappa\delta(u-u')\delta^{(2)}(z,z')$$

- Soft theorems are conservation laws $Q_\xi(\iota_0^+) = Q_\xi(\iota_0^-)$

- Recent analysis have shown that besides (M, P_A) higher spin symmetry are presents with charges $T_{AB}, F_{ABC}, \cdots$

Ana's talk



Lesson from ∞

- Asymptotic infinity also carry the structure of an asympotic fluid: Two generator of symmetry the mass aspect and angular momenta aspect.

$$GBMS = \mathrm{Diff}(S) \ltimes \mathbb{R}^S_{-1}$$

- Asymptotic infinity also carry the structure of an asympotic fluid: Two generators of symmetry the mass aspect M and angular momenta aspect P_A .
- Diff(S) rep are labelled by dimension and spin $(\Delta, \pm 2)$ with **angular momenta aspect**

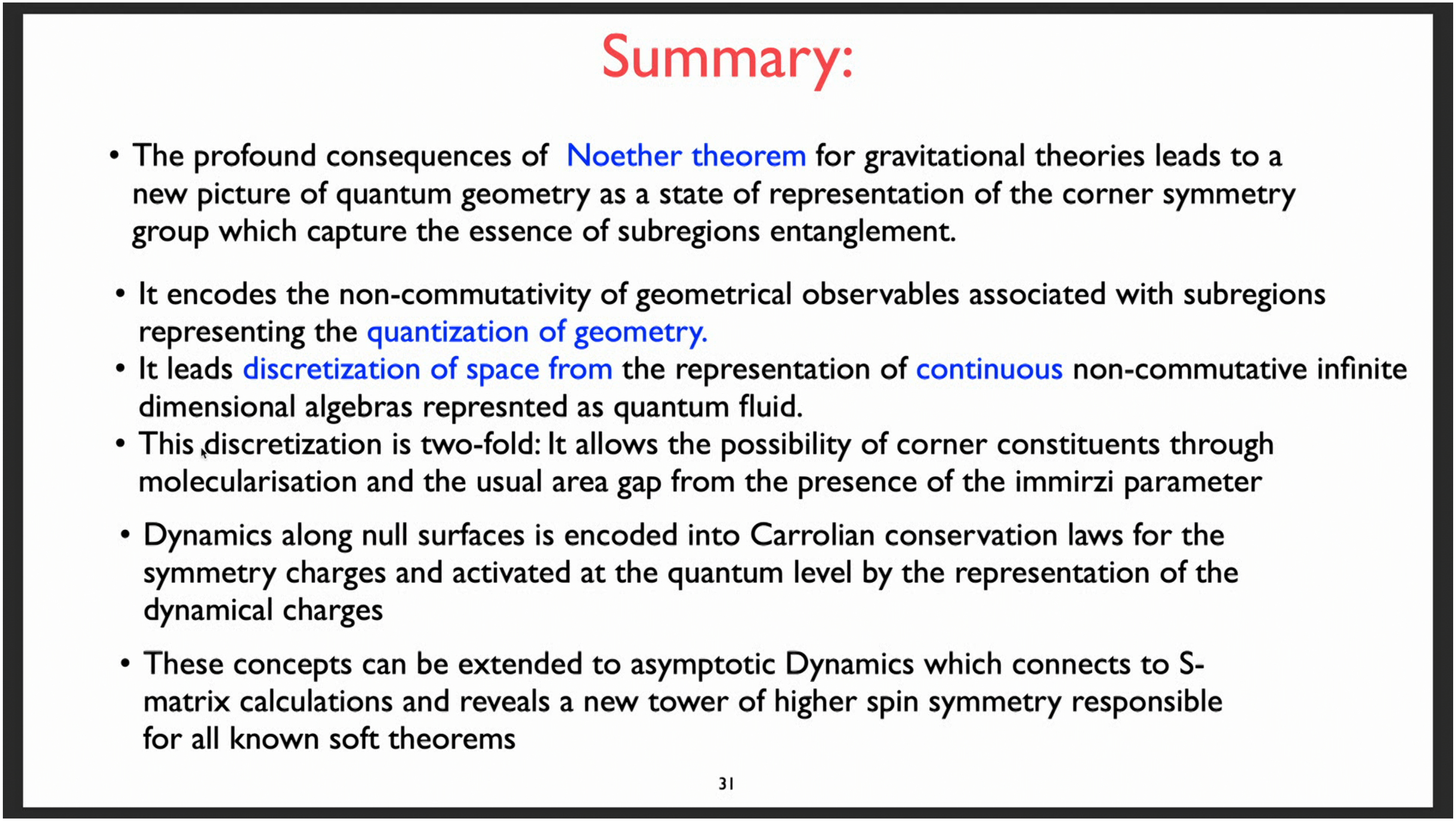
$$\boxed{P_A = \sum_i \delta^{(2)}(\sigma, \sigma_i) D_A + (\Delta_i \delta_A^B \pm 2\epsilon_A{}^B)\partial_B \delta^{(2)}(\sigma, \sigma_i)}$$

- The **mass aspect** plays the role of a density operator that shifts dimension

$$M = \sum_i \hat{M}_i \delta^{(2)}(\sigma, \sigma_i) \qquad M_i G_\Delta = G_{\Delta+1}$$

- The (Δ, s) representations = insertions of the conformal gravitons = constituents at ∞

$$G_{\Delta,\pm 2}(\sigma) = \int_{-\infty}^{+\infty} \mathrm{d}\omega \omega^{\Delta-1} a_\pm(\omega q(\sigma)) \qquad q^2 = 0$$



Summary:

- The profound consequences of Noether theorem for gravitational theories leads to a new picture of quantum geometry as a state of representation of the corner symmetry group which capture the essence of subregions entanglement.
- It encodes the non-commutativity of geometrical observables associated with subregions representing the quantization of geometry.
- It leads discretization of space from the representation of continuous non-commutative infinite dimensional algebras represnted as quantum fluid.
- This discretization is two-fold: It allows the possibility of corner constituents through molecularisation and the usual area gap from the presence of the immirzi parameter
- Dynamics along null surfaces is encoded into Carrolian conservation laws for the symmetry charges and activated at the quantum level by the representation of the dynamical charges
- These concepts can be extended to asymptotic Dynamics which connects to S-matrix calculations and reveals a new tower of higher spin symmetry responsible for all known soft theorems