Kinematical (Higher-Spin) Chern-Simons Theories

Stefan Prohazka
stefan.prohazka@ulb.ac.be

Université Libre de Bruxelles

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Collaborators

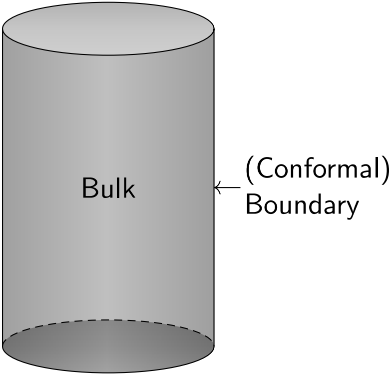
- Daniel Grumiller
- Eric Bergshoeff
- Jan Rosseel
- Javier Matulich
- José Figueroa-O'Farrill
- Max Riegler

1612.02277, 1710.11105 , 1710.11110, work in progress

Outline

Holographic Principle

- (Non-gravitational) Boundary theory $(D-1)$ could be sufficient to describe a (gravitational) bulk theory (D)
  ['t Hooft '93, Susskind '95]
- Realized:
  AdS/CFT correspondence
  [Maldacena '98]



How General is Holography?

- Holographic principle independent of AdS/CFT
- Insights of AdS/CFT correspondence beyond AdS and CFT?
- Field theories not always relativistic and conformal (condensed matter systems)
- AdS one possibility of many geometries
- Symmetry groups of space and time classified $\rightarrow$ kinematical algebras [Bacry, Lévy Leblond '67]

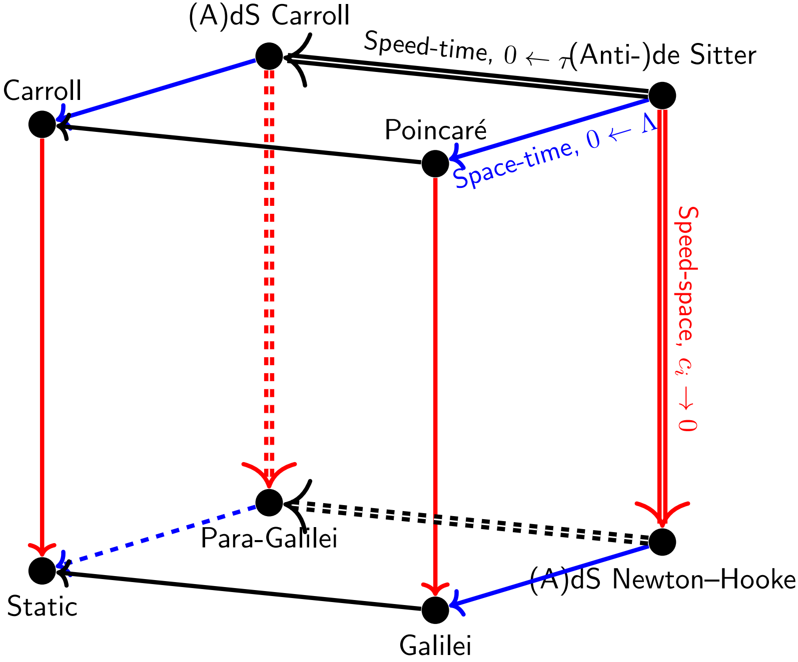
Outline

What are Kinematical Algebras?

- Kinematical Algebras: Take generators of $(D = 3 + 1)$
  - Time and space translations $\mathtt{H}$, $\mathtt{P}_i$
  - Spatial rotations $\mathtt{J}_i$
  - Inertial transformations $\mathtt{G}_i$
- Assumptions:
  - Space is isotropic

$$
\begin{aligned}
[\mathtt{J}_i, \mathtt{H}] &= 0 \\
[\mathtt{J}_i, \mathtt{J}_j] &= \epsilon_{ijk} \mathtt{J}_k \\
[\mathtt{J}_i, \mathtt{P}_j] &= \epsilon_{ijk} \mathtt{P}_k \\
[\mathtt{J}_i, \mathtt{G}_j] &= \epsilon_{ijk} \mathtt{G}_k
\end{aligned}
$$

  - Inertial transformations are noncompact
  - Parity and time-reversal are automorphisms
- Check for consistent Lie algebras
- This can be generalized in various ways (José)


(A)dS Carroll
Speed-time, $0 \leftarrow \tau$
(Anti-)de Sitter
Carroll
Poincaré
Space-time, $0 \leftarrow \Lambda$
Speed-space, $c_i \to 0$
Para-Galilei
Static
(A)dS Newton–Hooke
Galilei

Outline

Three spacetime dimensions

- Technically simpler $\rightarrow$ (maybe) useful for conceptual questions
- Good balance between complexity and tractability
  - AdS$_3$ no gravitational waves [Staruszkiewicz '63] but black holes [Bañados et al '92]
- Boundary theory possibility CFT$_2$ $\rightarrow$ high degree of analytical control
- Higher spin theories have an (easy) action

Chern–Simons Action

$$I_{\mathrm{CS}} = \frac{k}{4\pi}\int_{\mathrm{M}_3} \langle dA \wedge A + \frac{1}{3}[A, A] \wedge A \rangle \qquad A = A^a{}_\mu \, \mathtt{T}_a \otimes dx^\mu$$

Chern–Simons Action — Gauge Algebra

$$I_{\text{CS}} = \frac{k}{4\pi}\int_{\text{M}_3} \langle dA \wedge A + \frac{1}{3}[A, A] \wedge A\rangle \qquad A = A^a{}_\mu \, \mathtt{T}_a \otimes dx^\mu$$

- Gauge algebra $\mathfrak{g}$ with $[\mathtt{T}_a, \mathtt{T}_b] = f_{ab}{}^c \, \mathtt{T}_c$ describes the field content
  - Anti-de Sitter $\mathfrak{AdS} = \mathfrak{sl}(2, \mathbb{R}) \oplus \mathfrak{sl}(2, \mathbb{R})$

    $$I_{\text{CS}} \propto \int \sqrt{|g|}\left(R + \frac{2}{\ell^2}\right) d^3x$$

    where

    $$g_{\mu\nu} = \frac{1}{2}\langle A_\mu A_\nu \rangle$$

    and $\mathfrak{sl}(2, \mathbb{R})$

    $$[\mathtt{L}_n, \mathtt{L}_m] = (n - m)\,\mathtt{L}_{n+m} \qquad (n, m = \pm 1, 0)$$

  - De Sitter $\mathfrak{dS} = \mathfrak{sl}(2, \mathbb{C})$ and Poincaré $\mathfrak{poi}$

Chern–Simons Action — Gauge Algebra

$$I_{\mathrm{CS}} = \frac{k}{4\pi} \int_{\mathrm{M}_3} \langle dA \wedge A + \frac{1}{3} [A, A] \wedge A \rangle \qquad A = A^a{}_\mu \, \mathtt{T}_a \otimes dx^\mu$$

- Spin-3 on AdS $\mathfrak{sl}(3, \mathbb{R}) \oplus \mathfrak{sl}(3, \mathbb{R})$
- Interpretation: Spin-3 field coupled to gravity (hard in higher dimensions)

$$g_{\mu\nu} = \frac{1}{2} \langle A_\mu A_\nu \rangle \qquad \varphi_{\lambda\mu\nu} = \frac{1}{3!} \langle A_{(\lambda} A_\mu A_{\nu)} \rangle$$

- $\mathfrak{sl}(3, \mathbb{R})$

$$[\mathtt{L}_n, \, \mathtt{L}_m] = (n - m) \, \mathtt{L}_{n+m}$$
$$[\mathtt{L}_n, \, \mathtt{W}_m] = (2n - m) \, \mathtt{W}_{n+m}$$
$$[\mathtt{W}_n, \, \mathtt{W}_m] = -(n - m)(2n^2 + 2m^2 - nm - 8) \, \mathtt{L}_{n+m}$$

Chern–Simons Action — Gauge Algebra

$$I_{\mathrm{CS}} = \frac{k}{4\pi}\int_{\mathrm{M}_3}\langle dA\wedge A + \frac{1}{3}[A, A]\wedge A\rangle \qquad A = A^a{}_\mu\, \mathtt{T}_a \otimes dx^\mu$$

- Spin-3 gravity in metric formulation [Campoleoni et al. '13, ...]

$$\begin{aligned} I_{\mathrm{CS}} \propto \int d^3x\sqrt{|g|}\,\Bigg[\left(R+\frac{2}{\ell^2}\right) &+ \varphi^{\mu\nu\rho}\left(\mathcal{F}_{\mu\nu\rho} - \frac{3}{2}g_{(\mu\nu}\mathcal{F}_{\rho)}\right) \\ &- \frac{3}{2}R\varphi_{\mu\nu\rho}\varphi^{\mu\nu\rho} + \frac{9}{4}R_{\rho\sigma}\left(2\varphi^\rho{}_{\mu\nu}\varphi^{\sigma\mu\nu} - \varphi^\rho\varphi^\sigma\right) \\ &- \frac{1}{\ell^2}\left(6\varphi_{\mu\nu\rho}\varphi^{\mu\nu\rho} - 9\varphi_\mu\varphi^\mu\right)\Bigg] + \mathcal{O}(\varphi^4) \end{aligned}$$

- Nontrivial generalization of GR (new geometric understanding needed)
- Toy model for Vasiliev theory

Chern–Simons Action — Invariant Metric

$$I_{\mathrm{CS}} = \frac{k}{4\pi}\int_{\mathrm{M}_3} \langle dA \wedge A + \frac{1}{3}[A,A] \wedge A \rangle \qquad A = A^a{}_\mu \, \mathtt{T}_a \otimes dx^\mu$$

- Invariant metric is bilinear form $\langle \cdot, \cdot \rangle : \mathfrak{g} \times \mathfrak{g} \to \mathbb{R}$
  1. Symmetry:
  $$\langle X, Y \rangle = \langle Y, X \rangle \quad \text{for all} \quad X, Y \in \mathfrak{g}$$
  2. Non-degeneracy:
  $$\text{If} \quad \langle X, Y \rangle = 0 \quad \text{for all} \quad Y \in \mathfrak{g} \quad \text{then} \quad X = 0$$
  3. Invariance:
  $$\langle [Z, X], Y \rangle + \langle X, [Z, Y] \rangle = 0 \quad \text{for all} \quad X, Y, Z \in \mathfrak{g}$$
- Metric Lie algebras

Chern–Simons Action — Invariant Metric

$$I_{\text{CS}} = \frac{k}{4\pi}\int_{\text{M}_3} \langle dA \wedge A + \frac{1}{3}[A,A]\wedge A\rangle \qquad A = A^a{}_\mu\,\mathtt{T}_a \otimes dx^\mu$$

- Example: Trace for (semi)simple Lie algebras

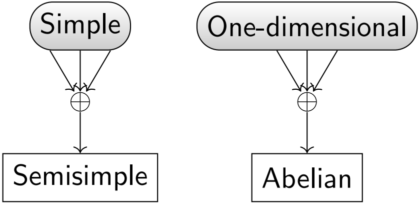
$$\mathtt{L}_{-1} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad \mathtt{L}_0 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \mathtt{L}_{+1} = \begin{pmatrix} 0 & 0 \\ -1 & 0 \end{pmatrix}$$

$$\langle \mathtt{L}_a \mathtt{L}_b \rangle = \text{Tr}(\mathtt{L}_a\,\mathtt{L}_b) = \left(\begin{array}{c|ccc} & \mathtt{L}_{-1} & \mathtt{L}_0 & \mathtt{L}_{+1} \\ \hline \mathtt{L}_{-1} & 0 & 0 & -1 \\ \mathtt{L}_0 & 0 & \frac{1}{2} & 0 \\ \mathtt{L}_{+1} & -1 & 0 & 0 \end{array}\right)$$

- Trace proportional to Killing form $\rightarrow$ Non-semisimple degenerate $\rightarrow$ Are there Lie algebras beyond semisimple?

Outline

Lie algebras with Invariant Metric [Medina, Revoy '85; Figueroa-O'Farrill, Stanciu '95]



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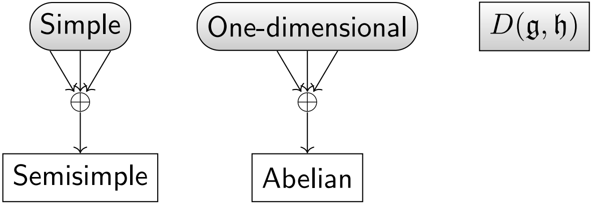

Double Extension $D(\mathfrak{g}, \mathfrak{h})$ [Medina, Revoy '85]

$D(\mathfrak{g}, \mathfrak{h})$ defined on the vector space $\mathfrak{g} \dot{+} \mathfrak{h} \dot{+} \mathfrak{h}^*$ by

$$[\mathtt{G}_i, \mathtt{G}_j] = {f_{ij}}^k \mathtt{G}_k$$

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$$[\mathtt{G}_i, \mathtt{G}_j] = f_{ij}{}^k \mathtt{G}_k$$

$$[\mathtt{H}_\alpha, \mathtt{G}_i] = f_{\alpha i}{}^j \mathtt{G}_j$$

$$[\mathtt{H}_\alpha, \mathtt{H}_\beta] = f_{\alpha\beta}{}^\gamma \mathtt{H}_\gamma$$

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$D(\mathfrak{g},\mathfrak{h})$ defined on the vector space $\mathfrak{g}\dot{+}\mathfrak{h}\dot{+}\mathfrak{h}^*$ by

$$
\begin{aligned}
[\mathtt{G}_i, \mathtt{G}_j] &= f_{ij}{}^k \mathtt{G}_k + f_{\alpha i}{}^k \Omega^{\mathfrak{g}}_{kj} \mathtt{H}^\alpha \\
[\mathtt{H}_\alpha, \mathtt{G}_i] &= f_{\alpha i}{}^j \mathtt{G}_j \\
[\mathtt{H}_\alpha, \mathtt{H}_\beta] &= f_{\alpha\beta}{}^\gamma \mathtt{H}_\gamma \\
[\mathtt{H}_\alpha, \mathtt{H}^\beta] &= -f_{\alpha\gamma}{}^\beta \mathtt{H}^\gamma \\
[\mathtt{H}^\alpha, \mathtt{G}_j] &= 0 \\
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\end{aligned}
$$

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$$
\begin{aligned}
[\mathtt{G}_i,\mathtt{G}_j] &= f_{ij}{}^k\mathtt{G}_k + f_{\alpha i}{}^k\Omega^{\mathfrak{g}}_{kj}\mathtt{H}^\alpha \\
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[\mathtt{H}_\alpha,\mathtt{H}_\beta] &= f_{\alpha\beta}{}^\gamma\mathtt{H}_\gamma \\
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[\mathtt{H}^\alpha,\mathtt{G}_j] &= 0 \\
[\mathtt{H}^\alpha,\mathtt{H}^\beta] &= 0
\end{aligned}
$$

It has the invariant metric

$$
\Omega^{\mathfrak{d}}_{ab} = \begin{array}{c} \\ \mathtt{G}_i \\ \mathtt{H}_\alpha \\ \mathtt{H}^\alpha \end{array}
\begin{array}{c} \begin{array}{ccc} \mathtt{G}_j & \mathtt{H}_\beta & \mathtt{H}^\beta \end{array} \\
\begin{pmatrix} \Omega^{\mathfrak{g}}_{ij} & 0 & 0 \\ 0 & h_{\alpha\beta} & \delta_\alpha{}^\beta \\ 0 & \delta^\alpha{}_\beta & 0 \end{pmatrix} \end{array}
$$

Double Extension $D(\mathfrak{g}, \mathfrak{h})$ [Medina, Revoy '85]

$D(\mathfrak{g}, \mathfrak{h})$ defined on the vector space $\mathfrak{g} \dot{+} \mathfrak{h} \dot{+} \mathfrak{h}^*$ by

$$
\begin{aligned}
[\mathtt{G}_i, \mathtt{G}_j] &= f_{ij}{}^k \mathtt{G}_k + f_{\alpha i}{}^k \Omega^{\mathfrak{g}}_{kj} \mathtt{H}^\alpha \\
[\mathtt{H}_\alpha, \mathtt{G}_i] &= f_{\alpha i}{}^j \mathtt{G}_j \\
[\mathtt{H}_\alpha, \mathtt{H}_\beta] &= f_{\alpha\beta}{}^\gamma \mathtt{H}_\gamma \\
[\mathtt{H}_\alpha, \mathtt{H}^\beta] &= -f_{\alpha\gamma}{}^\beta \mathtt{H}^\gamma \\
[\mathtt{H}^\alpha, \mathtt{G}_j] &= 0 \\
[\mathtt{H}^\alpha, \mathtt{H}^\beta] &= 0
\end{aligned}
$$

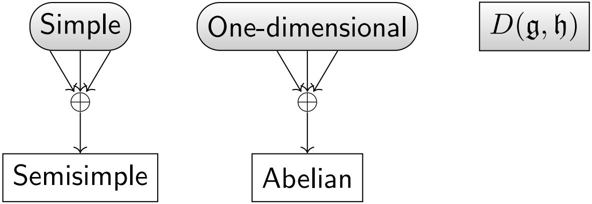
$D(0, \mathfrak{so}(2,1))$

$$
[\mathtt{J}_A, \mathtt{J}_B] = \epsilon_{AB}{}^C \mathtt{J}_C \qquad [\mathtt{J}_A, \mathtt{P}^B] = -\epsilon_{AC}{}^B \mathtt{P}^C \qquad [\mathtt{P}^A, \mathtt{P}^B] = 0
$$

and the invariant metric

$$
\langle \mathtt{J}_A, \mathtt{J}_B \rangle = \eta_{AB} \qquad \langle \mathtt{J}_A, \mathtt{P}^B \rangle = \delta_A{}^B \qquad \langle \mathtt{P}^A, \mathtt{P}^B \rangle = 0 \, .
$$

Lie algebras with Invariant Metric [Medina, Revoy '85; Figueroa-O'Farrill, Stanciu '95]



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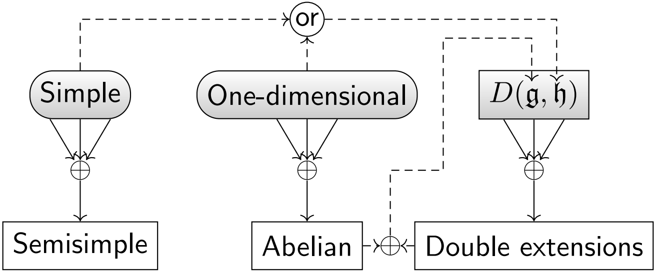

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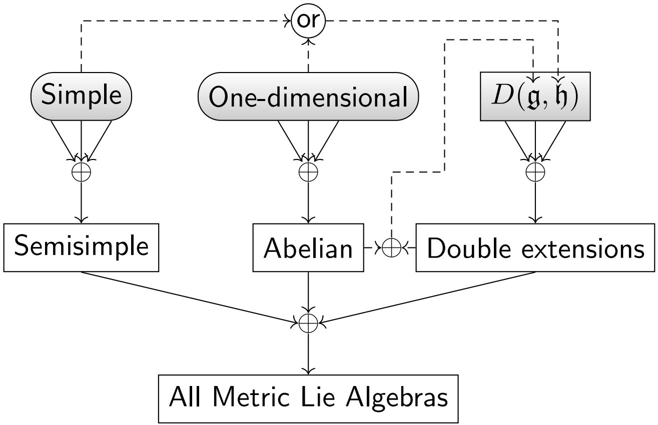


Outline

Kinematical Chern–Simons Theories

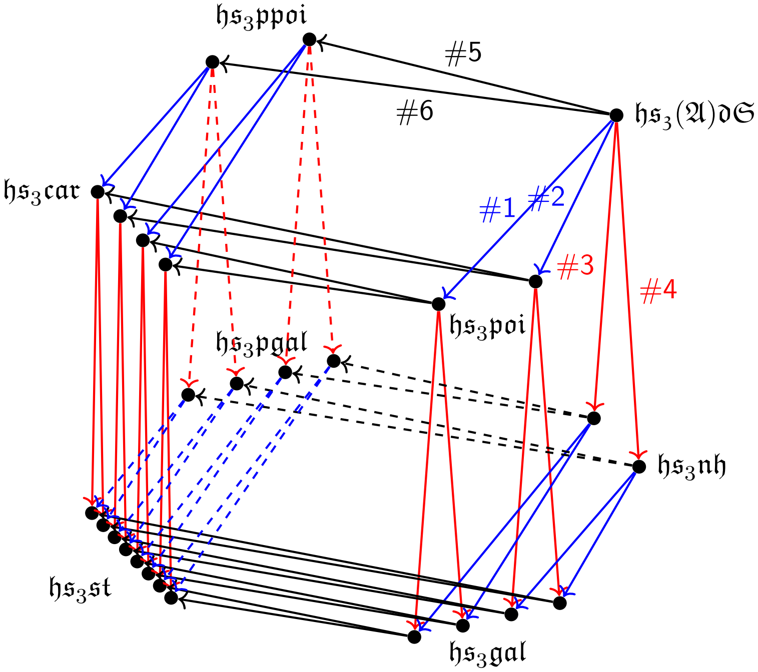
- So Lie algebras are sometimes metric, sometimes not $\rightarrow$ which of the kinematical Lie algebras are?
- Are they connected via contractions/approximations?
  - In general this restricts the class of possible invariant metrics,
  - In this case there is no loss of generality.
- Do the contractions also "work" on the level of the action?
  - Generically not

Kinematical Chern–Simons Theories

- What is the actual problem:
  - Start with (A)dS (rigid)
  - Contractions of Levy-Leblond, Bacry on the Lie algebra level
  - Does the invariant metric stay nondegenerate?
    - This means the action is still well defined
- "Contraction" not only on the Lie algebra level also on the invariant metric
  - Well defined contraction of Lie algebra and invariant metric $\rightarrow$ well defined contraction of the action $\rightarrow$ equation of motion !
  - Algebraic problem
- Constructive

Kinematical Higher Spin Theories

- Are there any?
- Use IW contractions:
  - Start with higher spin AdS, $\mathfrak{sl}(3,\mathbb{R}) \oplus \mathfrak{sl}(3,\mathbb{R})$
  - Restricted to spin-2 part $\rightarrow$ contraction should be that of kinematical algebras
  - Resulting contraction not all commutators of the spin-3 part are vanishing.
  - Under this conditions we classified the contractions



𝔥𝔰$_3$𝔭𝔭𝔬𝔦
#5
#6
𝔥𝔰$_3$(𝔄)𝔡𝔖
𝔥𝔰$_3$𝔠𝔞𝔯
#1
#2
#3
#4
𝔥𝔰$_3$𝔭𝔬𝔦
𝔥𝔰$_3$𝔭𝔤𝔞𝔩
𝔥𝔰$_3$𝔫𝔥
𝔥𝔰$_3$𝔰𝔱
𝔥𝔰$_3$𝔤𝔞𝔩

Non-AdS Higher Spin Gravity?

- Non-AdS Higher Spin Algebras ✓
- CS action would be nice

$$I_{\mathrm{CS}} = \frac{k}{4\pi} \int_{\mathrm{M}_3} \langle dA \wedge A + \frac{1}{3}[A, A] \wedge A \rangle$$

- Do Lie algebras have an invariant metric?
  - HS AdS$= \mathfrak{sl}(3,\mathbb{R}) \oplus \mathfrak{sl}(3,\mathbb{R}) \rightarrow$ semi-simple ✓
  - HS Poincaré $\rightarrow$ Double extension ✓
  - HS Poincaré $\rightarrow$ HS Carroll ✓
  - Invariant metric preserving contraction (natural generalization of IW contraction to double extensions)
  - HS Galilei ✗

HS Galilei: What can we do?

- Central extensions, but can be interpreted as double extensions
- Galilei double extension = Extended Bargmann algebra
- Naturally generalize spin-2 to higher spin Extended Bargmann algebras
- Not possible with only central extensions
- Theories analyzed on linear level [Bergshoeff '16]

Extended Bargmann 1 (Part I)

$$[\,\mathtt{J}\,,\,\mathtt{G}_a\,] = \epsilon_{am}\mathtt{G}_m \qquad [\,\mathtt{J}\,,\,\mathtt{P}_a\,] = \epsilon_{am}\mathtt{P}_m$$

$$[\,\mathtt{G}_a\,,\,\mathtt{H}\,] = -\epsilon_{am}\mathtt{P}_m$$

$$[\,\mathtt{G}_a\,,\,\mathtt{G}_b\,] = \epsilon_{ab}\mathtt{H}^* \qquad [\,\mathtt{P}_a\,,\,\mathtt{G}_b\,] = \epsilon_{ab}\mathtt{J}^*$$

$$[\,\mathtt{J}\,,\,\mathtt{J}_a\,] = \epsilon_{am}\mathtt{J}_m \qquad [\,\mathtt{J}\,,\,\mathtt{G}_{ab}\,] = -\epsilon_{m(a}\mathtt{G}_{b)m}$$

$$[\,\mathtt{J}\,,\,\mathtt{H}_a\,] = \epsilon_{am}\mathtt{H}_m \qquad [\,\mathtt{J}\,,\,\mathtt{P}_{ab}\,] = -\epsilon_{m(a}\mathtt{P}_{b)m}$$

$$[\,\mathtt{G}_a\,,\,\mathtt{J}_b\,] = -(\epsilon_{am}\mathtt{G}_{bm} + \epsilon_{ab}\mathtt{G}_{mm}) \qquad [\,\mathtt{G}_a\,,\,\mathtt{H}_b\,] = -(\epsilon_{am}\mathtt{P}_{bm} + \epsilon_{ab}\mathtt{P}_{mm})$$

$$[\,\mathtt{H}\,,\,\mathtt{J}_a\,] = \epsilon_{am}\mathtt{H}_m \qquad [\,\mathtt{H}\,,\,\mathtt{G}_{ab}\,] = -\epsilon_{m(a}\mathtt{P}_{b)m}$$

$$[\,\mathtt{P}_a\,,\,\mathtt{J}_b\,] = -(\epsilon_{am}\mathtt{P}_{bm} + \epsilon_{ab}\mathtt{P}_{mm})$$

Extended Bargmann 1 (Part II)

$$[\,\mathtt{J}_a\,,\,\mathtt{J}_b\,] = \epsilon_{ab}\mathtt{J}$$

$$[\,\mathtt{J}_a\,,\,\mathtt{G}_{bc}\,] = \delta_{a(b}\epsilon_{c)m}\mathtt{G}_m \qquad [\,\mathtt{J}_a\,,\,\mathtt{H}_b\,] = \epsilon_{ab}\mathtt{H}$$

$$[\,\mathtt{J}_a\,,\,\mathtt{P}_{bc}\,] = \delta_{a(b}\epsilon_{c)m}\mathtt{P}_m \qquad [\,\mathtt{G}_{ab}\,,\,\mathtt{H}_c\,] = -\delta_{c(a}\epsilon_{b)m}\mathtt{P}_m$$

$$[\,\mathtt{G}_{ab}\,,\,\mathtt{G}_{cd}\,] = \epsilon_{(a(c}\delta_{d)b)}\mathtt{H}^* \qquad [\,\mathtt{P}_{ab}\,,\,\mathtt{G}_{cd}\,] = \epsilon_{(a(c}\delta_{d)b)}\mathtt{J}^*$$

$$[\,\mathtt{P}_a\,,\,\mathtt{G}_{bc}\,] = \epsilon_{a(b}\mathtt{J}^*_{c)} \qquad [\,\mathtt{G}_a\,,\,\mathtt{G}_{bc}\,] = \epsilon_{a(b}\mathtt{H}^*_{c)}$$

$$[\,\mathtt{G}_a\,,\,\mathtt{P}_{bc}\,] = \epsilon_{a(b}\mathtt{J}^*_{c)} \qquad [\,\mathtt{J}\,,\,\mathtt{H}^*_a\,] = \epsilon_{am}\mathtt{H}^*_m$$

$$[\,\mathtt{J}\,,\,\mathtt{J}^*_a\,] = \epsilon_{am}\mathtt{J}^*_m \qquad [\,\mathtt{H}\,,\,\mathtt{H}^*_a\,] = \epsilon_{am}\mathtt{J}^*_m$$

$$[\,\mathtt{J}_a\,,\,\mathtt{J}^*\,] = -\epsilon_{am}\mathtt{J}^*_m \qquad [\,\mathtt{J}_a\,,\,\mathtt{H}^*\,] = -\epsilon_{am}\mathtt{H}^*_m$$

$$[\,\mathtt{J}_a\,,\,\mathtt{J}^*_b\,] = \epsilon_{ab}\mathtt{J}^* \qquad [\,\mathtt{J}_a\,,\,\mathtt{H}^*_b\,] = \epsilon_{ab}\mathtt{H}^*$$

$$[\,\mathtt{H}_a\,,\,\mathtt{H}^*\,] = -\epsilon_{am}\mathtt{J}^*_m \qquad [\,\mathtt{H}_a\,,\,\mathtt{H}^*_b\,] = \epsilon_{ab}\mathtt{J}^*$$

Outline

Summary

- Kinematical algebras + invariant metrics in $2+1$ dimension is rich (see also José)
- For Bacry and Levy-Leblond algebras + central extensions: Always well defined action + limit
- (Partially) generalizes to higher spin theories
- Contracted Lie algebras with invariant metric generically double extensions
- Spin-2 Extended Bargmann related to Hořava-Lifshitz gravity [Lei et al. '15] $\rightarrow$ Related to Spin-3 Hořava Gravity (?)

Outlook

- "Do everything that has been done for AdS_3"
  - A lot of tools available
  - Nonrelativistic (entanglement) entropy (Daniel, Alejandra)?
  - Holography: Maybe stick to negative cosmological constant (?)
- Solution space (Coset constructions)
- Boundary conditions (done for Carroll Spin-2)
- Boundary theories
  - Interesting math (Drinfeld Sokolov reduction for nonsemisimple Lie algebras)
- In general interesting math (non semisimple Lie algebras, but restricted to kinematical)
- Fronsdal-like equations for higher spins
- Lie superalgebras
  - Double superextensions
- Double extensions and deformations/contractions

Thank you very much for your attention.