Review Article

Noncommutative Relativistic Spacetimes and Worldlines from 2 + 1 Quantum (Anti-)de Sitter Groups

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1. Introduction

The connection between quantum groups and Planck scale physics was early suggested in [1]. Quantum deformations of Lie algebras and Lie groups [2–8] have been broadly applied in the construction of deformed symmetries of spacetimes [9–23], especially for the Poincaré and Galilei cases, for which the deformation parameter is known to play the role of a fundamental scale. Among all these quantum kinematical algebras the well known \(\kappa\)-Poincaré algebra [9, 13, 14, 16, 18] has been frequently considered.

These deformed Poincaré symmetries were later applied in the context of the so-called doubly special relativity (DSR) theories [24–32] which introduced two fundamental scales: the usual observer-independent velocity scale \(c\) as well as an observer-independent length scale \(l_p\), which was related to the deformation parameter in the algebra. Since from all approaches to quantum gravity [33–37] the Planck scale is thought to play a fundamental role, DSR theories seem to establish a promising link between some Planck scale effects and quantum groups [38, 39].

From a more general viewpoint, we recall that noncommutative spaces have been proposed as a suitable algebraic framework in order to describe the “quantum” structure of the geometry of spacetime at the Planck scale through a noncommutative algebra of quantum spacetime coordinates [40–44]. In this way the deformation parameter characterizes the noncommutativity of the spacetime algebra, thus generating uncertainty relations between noncommuting coordinates that can be thought to model a “fuzzy” or “discrete” nature of the spacetime at very small distances (or high energies) [45, 46]. In particular, the noncommutative spacetime deduced from the \(\kappa\)-Poincaré algebra is the so-called \(\kappa\)-Minkowski spacetime [15, 22], which is the algebra defined by the spacetime quantum group coordinates dual to the translation (momenta) generators.

In this framework, spacetime curvature (or nonzero cosmological constant) should play a relevant role concerning...
The possible cosmological consequences of a quantum spacetime (see, e.g., [38, 47–51] and references therein). Therefore, it seems natural to consider the construction of the $\kappa$-deformation for the (anti-)de Sitter (hereafter (A)dS) groups, and to analyse their possible connections with quantum gravity theories with a nonzero cosmological constant. In this respect, we recall that the Hopf structure for the $\kappa$-deformation of $(2 + 1)$D (A)dS and Poincaré ($\mathcal{P}$) algebras were collectively obtained in [19], and their connection between their deformed commutation rules and $2 + 1$ quantum gravity has been explored in [38]. The results obtained in [19] correspond to the l.h.s. of the commutative diagram:

$$
\begin{array}{cccc}
\text{AdS} & \xrightarrow{\omega \to \infty} & \text{Fun}(\text{AdS}) & \xrightarrow{\omega \to \infty} & \text{Fun}(\text{AdS}) \supset \text{AdS}^{2+1} \\
\text{ds} & \xrightarrow{\omega \to \infty} & \text{U}_{s}(\text{ds}) & \xrightarrow{\omega \to \infty} & \text{U}_{s}(\text{ds}) \supset \text{AdS}^{2+1} \\
\text{U}_{s}(\mathcal{P}) & \text{Duality} & \text{Fun}(\mathcal{P}) & \text{Fun}(\mathcal{P}) \supset \text{M}^{2+1} \\
\end{array}
$$

where vertical arrows indicate a classical deformation [52, 53] that introduces the spacetime curvature $\omega$ (or cosmological constant $\Lambda = -\omega$) related to the (A)dS radius $R$ by $\omega = \pm 1/R^2$, and the horizontal ones show the quantum deformation with parameter $z = 1/\kappa$ (related to the Planck length $\ell_P$); reversed arrows correspond to the spacetime contraction $\omega \to 0$ and (classical) nondeformed limit $z \to 0$. As a consequence, the construction of noncommutative (A)dS spacetimes in terms of intrinsic and ambient spacetime quantum group coordinates seems worth being explored in detail and, moreover, the same framework could account for new proposals of noncommutative spaces of time-like geodesics (worldlines), which, to the best of our knowledge, have not been considered in the literature yet, even for the Poincaré case.

Here we present an enlarged and updated review version of our unpublished manuscript arXiv:hep-th/0401244, in which the above-mentioned problems are faced for the three relativistic cases simultaneously, that is, by dealing explicitly with the spacetime curvature $\omega$ as a contraction parameter. Hence, we propose to explore the r.h.s. of the diagram (1) (dual to the r.h.s.) by computing the quantum deformation of the $(2 + 1)$D (A)dS groups (that is, Fun$_s((\text{A})\text{dS}))$ which are obtained by quantizing the Poisson–Lie algebra of smooth functions on these groups (namely, Fun$((\text{A})\text{dS}))$ coming from a suitable classical $r$-matrix. In this way, the $(2 + 1)$D noncommutative spaces (e.g., AdS$_{2+1}^\kappa$) can then be identified as certain subalgebras of the corresponding quantum groups. Moreover, we also construct and study in detail the corresponding 4D noncommutative spaces of worldlines. We stress that in our approach all the $\kappa$-Poincaré relations (including its noncommutative spaces) can be directly recovered from the general (A)dS expressions through the limit $\omega \to 0$. Moreover, all of the resulting noncommutative spaces are covariant under quantum group (co)actions (for the construction of Poisson and quantum homogeneous spaces we refer to [54–58] and references therein).

The structure of the paper is the following. In the next section we recall the basics on the (A)dS groups in $(2 + 1)$ dimensions and their associated homogeneous $(2 + 1)$D spacetimes and 4D spaces of worldlines (time-like lines). Both types of spaces are described in terms of intrinsic quantities (related to group parameters) as well as in ambient coordinates with one and two extra dimensions, respectively, which will be further used in their noncommutative versions. By starting from the classical $r$-matrix that generates the $\kappa$-deformation, we construct in Section 3 the corresponding Drinfeld–double and obtain some preliminary information on the first-order quantum deformation, from which first-order noncommutative spaces arise. On one hand, we find that at first-order in the deformation parameter the three noncommutative relativistic spacetimes are given by the same $\kappa$-Minkowski algebra. Moreover, we show that the deformation parameter can be interpreted as a curvature on a classical dS spacetime for the three cases, thus generalizing the results obtained in [29, 30] for $\kappa$-Poincaré. On the other hand, we obtain that the first-order noncommutative spaces of worldlines are in fact nondeformed ones, and a relationship with the nonrelativistic (Newtonian) kinematical groups is thus established.

As an intermediate stage in the search of the quantum (A)dS groups, we compute in Section 4 the invariant (A)dS vector fields and next the Poisson–Lie structures coming from the classical $r$-matrix generating the $\kappa$-deformation. These results enable us to propose in Section 5 the noncommutative (A)dS spaces, which are written in both intrinsic and ambient coordinates. The resulting noncommutative spacetimes show how the curvature modifies the underlying first-order $\kappa$-Minkowski space, while for the noncommutative spaces of worldlines we find that 2D velocity/rapidity space (spanned by the dual coordinates to the boost generators) remains nondeformed for $\kappa$-Poincaré but becomes deformed for the (A)dS cases. Hence Lorentz invariance seems to be lost (or somewhat “deformed”) when a nonzero curvature/cosmological constant is considered.

Section 6 is devoted to study the (dual) quantum (A)dS algebras and their deformed Casimirs in two different bases. In particular, starting from the expressions given in [19], a nonlinear transformation involving the generators of the stabilizer subgroup of a time-like line allows us to obtain these quantum algebras in a new basis that generalizes for any $\omega$ the bicrossproduct basis of $\kappa$-Poincaré [16]. These results are analysed in connection with $2 + 1$ quantum gravity [38] and a “duality” between curvature/cosmological constant and deformation parameter/Planck length is suggested along the same lines of the so-called “semidualization” approach for Hopf algebras in $2 + 1$ quantum gravity [59] associated with the exchange of the cosmological length scale and the Planck mass (see also [60, 61]). Finally, some remarks and comments concerning recent findings in this framework close the paper.

2. (Anti-)de Sitter Lie Groups and Their Homogeneous Spaces

The Lie algebras of the three $(2 + 1)$D relativistic spacetimes of constant curvature can collectively be described by means of...
a real (graded) contraction parameter $\omega$ [19], and we denote them by $so_\omega(2, 2)$. If $\{J, P_0, P = (P_1, P_2), K = (K_1, K_2)\}$ are, in this order, the generators of rotations, time translations, space translations, and boosts, the commutation relations of $so_\omega(2, 2)$ read

\[
\begin{align*}
[J, P_i] &= \epsilon_{ij} P_j, \\
[J, K_i] &= \epsilon_{ij} K_j, \\
[J, P_0] &= 0, \\
[P_i, K_j] &= -\delta_{ij} P_0, \\
[P_0, K_i] &= -P_i, \\
[K_1, K_2] &= -J, \\
[P_0, P_i] &= \omega K_i, \\
[P_i, P_j] &= -\omega J,
\end{align*}
\]

(2)

where from now on we assume that Latin indices $i, j = 1, 2$, Greek ones $\mu, \nu = 0, 1, 2$, $h = c = 1$, and $\epsilon_{ij}$ is a skew symmetric tensor such that $\epsilon_{12} = 1$. For a positive, zero, and negative value of $\omega$, $so_\omega(2, 2)$ provides a Lie algebra isomorphic to $so(2, 2), iso(2, 1)$, and $so(3, 1)$, respectively. The case $\omega = 0$ can also be understood as an Inönü–Wigner contraction [62]: $so(2, 2) \rightarrow iso(2, 1) \rightarrow so(3, 1)$.

Parity $\Pi$ and time-reversal $\Theta$ are involutive automorphisms of $so_\omega(2, 2)$ defined by [63]

\[
\begin{align*}
\Pi : (P_0, P, K, J) &\rightarrow (P_0, -P, -K, J), \\
\Theta : (P_0, P, K, J) &\rightarrow (-P_0, P, -K, J),
\end{align*}
\]

(3)

which together with the composition,

\[
\Pi \Theta : (P_0, P, K, J) \rightarrow (-P_0, -P, K, J),
\]

(4)

and the identity determine a $\mathbb{Z}_2 \otimes \mathbb{Z}_2 \otimes \mathbb{Z}_2$ Abelian group of involutions [64]. The automorphisms $\Pi \Theta$ and $\Pi$ give rise, in this order, to the Cartan decompositions:

\[
so_\omega(2, 2) = h_{(1)} \oplus p_{(1)},
\]

(5)

\[
h_{(1)} = \langle K, J \rangle = so(2, 1), \quad p_{(1)} = \langle P_0, P \rangle,
\]

\[
so_\omega(2, 2) = h_{(2)} \oplus p_{(2)},
\]

(6)

\[
h_{(2)} = \langle J, P_0 \rangle = so(2) \oplus so_\omega(2), \quad p_{(2)} = \langle P, K \rangle,
\]

where $h_{(1)} = so(2, 1)$ is the Lorentz subalgebra and $so_{\omega}(2) = \langle P_0 \rangle$ covers the Lie subalgebras $so(2), iso(1) = \mathbb{R}$, and $so(1, 1)$ for $\omega >, =, < 0$, correspondingly. In fact, the contraction parameter $\omega$ is related to the $\mathbb{Z}_2$ grading associated to $\Pi \Theta$.

When the Lie group $SO_{\omega}(2, 2)$ is considered, two relevant families of symmetric homogeneous spaces [65] can be constructed as follows.

(i) The $(2 + 1)$D spacetime: this is a rank 1 space, associated with the automorphism $\Pi \Theta$ (4) and Cartan decomposition (5), which is defined through the quotient

\[
S_{(1)} = \frac{SO_{\omega}(2, 2)}{SO(2, 1)},
\]

(7)

where $SO(2, 1)$ is the Lorentz subgroup spanned by $J$ and $K$.

Thus momenta $P_\mu$ characterize the tangent space at the origin. This space turns out to have constant curvature equal to the contraction parameter: $\omega = \pm 1/R^2$ for (A)dS and $\omega = 0$ ($R \rightarrow \infty$) for Minkowski, where $R$ is the universe radius.

(ii) The 4D space of time-like lines (or wordlines): this is a rank 2 space, related to the automorphism $\Pi$ (3) and Cartan decomposition (6), which is given by

\[
S_{(2)} = \frac{SO_{\omega}(2, 2)}{(SO(2) \otimes SO_{\omega}(2))},
\]

(8)

where $SO(2) = \langle J \rangle$ and $SO_{\omega}(2) = \langle P_0 \rangle$. This space is of hyperbolic type as this has constant curvature equal to $-1$ (i.e., $-1/c^2$ in terms of the speed of light). The tangent space is determined by spatial momenta $P$ and boosts $K$. In fact, $S_{(2)}$ can also be interpreted as a $(2 \times 2)$D relativistic phase space [66] in which position and momentum coordinates are related to the group parameters dual to $P$ and $K$, respectively.

We display in Table 1 each of the above symmetrical homogeneous spaces for each of the three Lorentzian Lie groups.

Table 1: The AdS, Minkowskian, and dS $(2 + 1)$D spacetimes and 4D spaces of time-like lines according to the curvature/cosmological constant $\omega = -\Lambda$.

<table>
<thead>
<tr>
<th>$\omega$, $\Lambda$</th>
<th>Spacetime $S_{(1)}$, with curvature $\omega$</th>
<th>Space of worldlines $S_{(2)}$, with curvature $-1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega &gt; 0$, $\Lambda &lt; 0$</td>
<td>$AdS^{2+1} = SO(2, 2)/SO(2, 1)$</td>
<td>$LAdS^{2+1} = SO(2, 2)/(SO(2) \otimes SO(2))$</td>
</tr>
<tr>
<td>$\omega = \Lambda = 0$</td>
<td>$M^{2+1} = ISO(2,1)/SO(2,1)$</td>
<td>$LM^{2+1} = ISO(2,1)/(SO(2) \otimes \mathbb{R})$</td>
</tr>
<tr>
<td>$\omega &lt; 0$, $\Lambda &gt; 0$</td>
<td>$dS^{2+1} = SO(3,1)/SO(2,1)$</td>
<td>$LdS^{2+1} = SO(3,1)/(SO(2) \otimes SO(1,1))$</td>
</tr>
</tbody>
</table>

On the other hand, the two Casimir invariants of the Lie algebra $so_\omega(2, 2)$ are given by

\[
\mathcal{C} = P_0^2 - \mathbf{p}^2 + \omega (J^2 - K^2),
\]

(9)

\[
\mathcal{W} = -P_0 + K_1 P_2 - K_2 P_1,
\]

where $\mathbf{p}^2 = P_1^2 + P_2^2$ and $K^2 = K_1^2 + K_2^2$. Recall that $\mathcal{C}$ comes from the Killing–Cartan form, while $\mathcal{W}$ is the Pauli–Lubanski vector.

2.1. Vector Model of the $(2 + 1)$D Relativistic Spacetimes. The action of the (A)dS groups on the homogeneous spaces that
we have just described is not linear. As it is well known, this problem can be circumvented by considering the vector representation of the Lie group $SO_\omega(2,2)$ which makes use of an ambient space with an “extra” dimension. In particular, the 4D real matrix representation of $so_\omega(2,2)$, given by

\[
P_0 = \begin{pmatrix}
0 & -\omega & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix},
\]
\[
P_1 = \begin{pmatrix}
0 & 0 & \omega & 0 \\
0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix},
\]
\[
P_2 = \begin{pmatrix}
0 & 0 & 0 & \omega \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0
\end{pmatrix},
\]
\[
J = \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 \\
0 & 0 & 1 & 0
\end{pmatrix},
\]
\[
K_1 = \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix},
\]
\[
K_2 = \begin{pmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix},
\]

fulfills

\[
Y^T I_{(1)} + I_{(1)} Y = 0,
\]

\[
Y \in so_\omega(2,2), \quad I_{(1)} = \text{diag}(1, \omega, -\omega, -\omega)
\]

($Y^T$ is the transpose of $Y$). The exponential of (10) leads to the vector representation of $SO_\omega(2,2)$ as a Lie group of matrices which acts linearly in a 4D space with ambient (or Weierstrass) coordinates $(s_3, s_\mu)$. The one-parameter subgroups of $SO_\omega(2,2)$ obtained from (10) turn out to be

\[
e^{x P_0} = \begin{pmatrix}
\cos \rho x_0 & -\rho \sin \rho x_0 & 0 & 0 \\
\frac{1}{\rho} \sin \rho x_0 & \cos \rho x_0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\]
\[
e^\theta J = \begin{pmatrix}
\cosh \rho x_1 & 0 & \rho \sinh \rho x_1 & 0 \\
0 & 1 & 0 & 0 \\
\frac{1}{\rho} \sinh \rho x_1 & 0 & \cosh \rho x_1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\]
\[
e^{x P_1} = \begin{pmatrix}
\cosh \rho x_1 & 0 & \rho \sinh \rho x_1 & 0 \\
0 & 1 & 0 & 0 \\
\frac{1}{\rho} \sinh \rho x_1 & 0 & \cosh \rho x_1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\]
\[
e^{x P_2} = \begin{pmatrix}
\cosh \rho x_2 & 0 & 0 & \rho \sinh \rho x_2 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
\frac{1}{\rho} \sinh \rho x_2 & 0 & 0 & \cosh \rho x_2
\end{pmatrix},
\]
\[
e^{x K_1} = \begin{pmatrix}
\cosh \xi_1 & 0 & \rho \sinh \xi_1 & 0 \\
0 & \cosh \xi_1 & \rho \sinh \xi_1 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\]
\[
e^{x K_2} = \begin{pmatrix}
\cosh \xi_2 & 0 & \rho \sinh \xi_2 & 0 \\
0 & \cosh \xi_2 & \rho \sinh \xi_2 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\]

where hereafter we also express the curvature as $\omega = \rho^2$. Hence, $\rho = 1/R$ and $\rho = i/R$ for $AdS_2+1$ and $dS_2+1$, while the (constriction) limit $\rho \to 0$ gives rise to $M^{2+1}$.

Any element $G \in SO_\omega(2,2)$ verifies that $G^T I_{(1)} G = I_{(1)}$. The $(2+1)$D spacetime $S(1)$ is identified with the orbit of the origin of the spacetime $O = (s_3, s_\mu) = (1,0,0,0)$ which is contained in the pseudosphere provided by $I_{(1)}$:

\[
\Sigma_{(1)} : s_3^2 + \omega (s_0^2 - s_3^2) = 1,
\]
where \( s^2 = s_1^2 + s_2^2 \). The metric on \( S_{(1)} \) comes from the flat ambient metric divided by the curvature and restricted to the above constant:

\[
d\sigma^2_{(1)} = \frac{1}{\omega} \left( ds_1^2 + \omega \left( ds_0^2 - ds_1^2 - ds_2^2 \right) \right) \bigg|_{\Sigma_{(1)}} = ds_0^2 - ds_1^2 - ds_2^2 + \omega \left( s_0 d_0 - s_1 d_1 - s_2 d_2 \right)^2 \frac{1}{1 - \omega \left( s_0^2 - s_1^2 - s_2^2 \right)}.
\]

Ambient coordinates can be parametrized in terms of three intrinsic spacetime coordinates in different ways. We shall introduce the geodesic parallel coordinates on the origin:

\[
(\rho, \sigma, \omega) \rightarrow \left( s_1, s_2, s_3 \right) = \exp \left( x_0 P_0 \right) \exp \left( x_1 P_1 \right) \exp \left( x_2 P_2 \right) O;
\]

namely,

\[
\begin{align*}
    s_3 &= \cos \rho x_3 \cos \rho x_1 \cos \rho x_2, \\
    s_0 &= \frac{\sin \rho x_0}{\rho} \cos \rho x_1 \cos \rho x_2, \\
    s_1 &= \frac{\sin \rho x_1}{\rho} \cos \rho x_2, \\
    s_2 &= \frac{\sin \rho x_2}{\rho}.
\end{align*}
\]

The role of the coordinates \( x_\mu \) that parametrize a generic point \( Q \) under (16) in the \((2 + 1)D\) spacetime is the following. Let \( l_0 \) be a time-like geodesic and \( l_1, l_2 \) two space-like geodesics such that these three basic geodesics are orthogonal at \( O \). Then \( x_0 \) is the geodesic distance from \( O \) up to a point \( Q_1 \) measured along \( l_0 \); \( x_1 \) is the distance between \( Q_1 \) and another point \( Q_2 \) along a space-like geodesic \( l_1' \) orthogonal to \( l_0 \) through \( Q_1 \) and parallel to \( l_1 \); and \( x_2 \) is the distance between \( Q_2 \) and \( Q \) along a space-like geodesic \( l_2' \) orthogonal to \( l_1' \) and parallel to \( l_2 \). Recall that time-like geodesics (as \( l_0 \)) are compact in \( \text{AdS}^{2+1} \) and noncompact in \( \text{dS}^{2+1} \), while space-like ones (as \( l_1, l_2 \)) are compact in \( \text{dS}^{2+1} \) but noncompact in \( \text{AdS}^{2+1} \). Thus the trigonometric functions depending on \( x_0 \) are circular in \( \text{AdS}^{2+1} (\rho = 1/R) \) and hyperbolic in \( \text{dS}^{2+1} (\rho = i/R) \) and, conversely, those depending on \( x_i \) are circular in \( \text{dS}^{2+1} \) but hyperbolic in \( \text{AdS}^{2+1} \).

Under (16), the metric (14) now reads

\[
d\sigma^2_{(1)} = \cosh^2 (\rho x_0) \cosh^2 (\rho x_1) \cosh^2 (\rho x_2) \, dx_0^2 - \cosh^2 (\rho x_2) \, dx_1^2 - dx_2^2.
\]

Notice that if \( \rho \to 0 \), the parametrization (16) gives the flat Cartesian coordinates \( s_3 = 1, s_x = x_\mu \), and the metric (17) reduces to \( d\sigma^2_{(1)} = dx_0^2 - dx_1^2 - dx_2^2 \) in \( \mathbb{M}^{2+1} \).

2.2. Bivector Model of the 4D Spaces of Worldlines. The action of \( SO_\omega(2, 2) \) on the space of time-like lines \( S_{(2)} \) is also a nonlinear one. As in the previous case, this problem can be solved by introducing an ambient space, now 6D with two “extra” dimensions, on which the group acts linearly and where \( S_{(2)} \) is embedded. Let us consider the so-called bivector representation of (2) given by [66]

\[
\begin{align*}
    P_0 &= -\omega e_{23} + e_{42} - \omega e_{35} + e_{53}, \\
    J &= -e_{23} + e_{32} - e_{45} + e_{54}, \\
    P_1 &= -\omega e_{14} - e_{41} + \omega e_{36} + e_{63}, \\
    K_1 &= e_{12} + e_{21} + e_{56} + e_{65}, \\
    P_2 &= -\omega e_{15} - e_{51} - \omega e_{26} - e_{62}, \\
    K_2 &= e_{13} + e_{31} - e_{46} - e_{64},
\end{align*}
\]

where \( e_{ab} \) is the 6×6 matrix with entries \( (e_{ab})_{ij} = \delta_{ai}^b \delta_{bj} \). Under this representation any generator \( Y \in so_\omega(2, 2) \) fulfills

\[
Y^T l_{(2)} + l_{(2)} Y = 0,
\]

where \( Y_{ii} = \eta_i^2 + \eta_i^2 \) and \( \eta_i^2 = y_i^2 + y_i^2 \). The metric on \( S_{(2)} \) follows from the 6D flat ambient metric divided by the negative curvature of \( S_{(2)} \) and subjected to both conditions (20):

\[
d\sigma^2_{(2)} = \frac{1}{\omega} \left( d\eta_1^2 - d\eta_2^2 - d\eta_3^2 - d\eta_4^2 - \omega \left( d\eta_5^2 - d\eta_6^2 \right) \right) \bigg|_{\Sigma_{(2)}, P}.
\]

Plücker coordinates can be expressed through four intrinsic quantities of \( S_{(2)} \). We shall consider the space \( x \) and rapidity (boost) \( \xi \) group coordinates. The action of the following sequence of one-parameter subgroups on \( \Theta \) (those defining the tangent space to \( S_{(2)} \)) under the representation (18),

\[
(\eta_3, \eta, y, y_3) (x, \xi) = \exp (x_1 P_1) \exp (x_2 P_2) \exp (\xi_1 K_1) \exp (\xi_2 K_2) \Theta,
\]
gives rise to
\[
\begin{align*}
\eta_3 &= \cosh \rho x_1 \cosh \rho x_2 \cosh \xi_1 \cosh \xi_2, \\
\eta_1 &= \cosh \rho x_2 \sinh \xi_1 \cosh \xi_2, \\
\eta_2 &= \cosh \rho x_1 \sinh \xi_2 \\
&\quad - \sinh \rho x_1 \sinh \rho x_2 \sinh \xi_1 \cosh \xi_2, \\
y_1 &= -\frac{\sinh \rho x_1}{\rho} \cosh \rho x_2 \cos \xi_1 \cosh \xi_2, \\
y_2 &= -\frac{\sinh \rho x_2}{\rho} \cosh \xi_1 \cosh \xi_2, \\
y_3 &= \frac{\sinh \rho x_1}{\rho} \sinh \xi_2 \\
&\quad - \cosh \rho x_1 \sinh \rho x_2 \sinh \xi_1 \cosh \xi_2.
\end{align*}
\] (23)

Under the contraction \( \rho \to 0 \) (\( \omega = 0 \)), this parametrization reduces to that of the 4D Minkowskian space of worldlines \( \text{LM}^{2\times 2} \):
\[
\begin{align*}
\eta_3 &= \cosh \xi_1 \cosh \xi_2, \\
y_3 &= x_1 \sinh \xi_2 - x_2 \sinh \xi_1 \cosh \xi_2, \\
\eta_1 &= \sinh \xi_1 \cosh \xi_2, \\
y_1 &= -x_1 \cosh \xi_1 \cosh \xi_2, \\
\eta_2 &= \sinh \xi_2, \\
y_2 &= -x_2 \cosh \xi_1 \cosh \xi_2.
\end{align*}
\] (24)

Such expressions indicate that the Plücker coordinates \((y, y_3)\) and \((\eta, \eta_3)\) can be interpreted as “position-like” and “momentum-like” ones, respectively, within the phase space \((x, \xi)\) \[66\]. In \( \text{LM}^{2\times 2} \) the metric (21) is degenerate and reads
\[
\begin{align*}
d\sigma^2_{(2)} &= \frac{\eta_1 d\eta_1 + \eta_2 d\eta_2}{1 + \eta^2} \\
&= \cosh^2 \xi_2 d\xi_2^2 + d\xi_2^2,
\end{align*}
\] (25)

which corresponds to a 2D space of rank 1 with negative curvature; that is, the 2D velocity Minkowskian space (so with coordinates \(\xi\)) is hyperbolic. Nevertheless, we stress that this is no longer true when \(\omega \neq 0\) (in both \( \text{LAdS}^{2\times 2} \) and \( \text{LdS}^{2\times 2} \)) where the complete \((2 \times 2)\) space structure is required (so with the four coordinates \((x, \xi)\)), thus precluding the possibility of using a “reduced” 2D velocity space.

3. (Anti-)de Sitter Drinfel’d-Doubles and First-Order Noncommutative Spaces

The first-order deformation terms in the coproduct of the \(\kappa\)-Poincaré algebra \([9, 13–18, 22]\) are known to be generated by the following classical \(r\)-matrix:
\[
r = z (K_1 \wedge P_1 + K_2 \wedge P_2),
\] (26)

where \(\wedge\) denotes the skew symmetric tensor product. Recall that \(r\) is a solution of the modified classical Yang–Baxter equation and that \(z\) is related to the usual \(\kappa\) and \(q\) deformation parameters by \(z = 1/\kappa = 1/q\).

Such a classical \(r\)-matrix also holds for the \(\text{(A)dS}\) algebras \([68]\), so that we shall consider (26) for the whole family \(s_o(2, 2)\). Hence this element gives rise to the cocommutator \(\delta\) of any generator \(Y_i\) through the relation \(\delta(Y_i) = [Y_i \otimes 1 + 1 \otimes Y_i, r]\); namely,
\[
\begin{align*}
\delta (P_i) &= 0, \\
\delta (J) &= 0, \\
\delta (P_i) &= z (P_i \wedge P_o - \omega \varepsilon_{ij} K_j \wedge J), \\
\delta (K_i) &= z (K_i \wedge P_o + \varepsilon_{ij} P_j \wedge J).
\end{align*}
\] (27)

Next if we denote by \(\bar{y}^i\) the quantum group coordinate dual to \(Y_i\), such that \(\langle \bar{y}^i \mid Y_j \rangle = \delta_{ij}\), and write the cocommutators as \(\delta(Y_i) = f_{jk}^i Y_j \wedge Y_k\), then Lie bialgebra duality provides the so-called Drinfel’d-double Lie algebra \([7, 8]\) formed by three sets of brackets: the initial Lie algebra, the dual relations, and the crossed commutation rules; namely,
\[
\begin{align*}
[Y_i, Y_j] &= \varepsilon_{ij} K_k, \\
[\bar{y}^i, \bar{y}^j] &= f_{jk}^i \bar{y}^k, \\
[\bar{y}^i, Y_j] &= \varepsilon_{ik} \bar{y}^k - f_{ik}^j Y_k.
\end{align*}
\] (28)

The cocycle condition for the cocommutator \(\delta\) implies the following compatibility equations among the structure constants \(\varepsilon_{ij}\) and \(f_{jk}^i\):
\[
\begin{align*}
f_{jk}^i &\varepsilon_{ij} = f_{ik}^a \varepsilon_{aj} + f_{jk}^b \varepsilon_{ib} + f_{jk}^c \varepsilon_{ic} + f_{jk}^d \varepsilon_{id}.
\end{align*}
\] (29)

In our case, we denote by \([\hat{\theta}, \hat{x}_\mu, \hat{\xi}_\mu]\) the dual noncommutative coordinates of the generators \([J, P_x, K_x]\), respectively. Thus the \(\text{(A)dS}\) and Poincaré Drinfel’d-doubles are collectively given in terms of the curvature \(\omega\) and deformation parameter \(z\) by the initial Lie algebra \(s_o(2, 2)\) (2), the dual commutators,
\[
\begin{align*}
[\hat{\theta}, \hat{x}_\mu] &= z \varepsilon_{ij} \hat{x}_j, \\
[\hat{x}_\mu, \hat{x}_\nu] &= -z \varepsilon_{ij} \hat{x}_j, \\
[\hat{x}_\mu, \hat{x}_2] &= 0, \\
[\hat{\theta}, \hat{x}_2] &= 0, \\
[\hat{\theta}, \hat{\xi}_\mu] &= -z \varepsilon_{ij} \hat{x}_j, \\
[\hat{x}_\mu, \hat{\xi}_\mu] &= -z \hat{\xi}_\mu, \\
[\hat{\xi}_\mu, \hat{\xi}_\nu] &= 0, \\
[\hat{x}_\mu, \hat{\xi}_\mu] &= 0, \\
[\hat{x}_\mu, \hat{\xi}_2] &= 0.
\end{align*}
\] (30)
which coincide with the \(\kappa\)-Minkowski space, \(M_{z}^{2+1}\) \([15–18]\), for any value of the curvature \(\omega\). As we shall see in Section 5, further corrections of (33) depending on \(\omega\) will appear when the full quantum (A)dS groups are considered.

As it was already studied in \([29, 30]\), the action of the generators on the noncommutative spacetime follows by replacing formally \(P_{\mu} \rightarrow \hat{x}_{\mu}\), which requires considering the commutators involving \(\{J, \hat{x}_{\mu}, K_{\nu}\}\) within the Drinfel'd-double. Next the change of basis given by \([30]\)

\[
\begin{align*}
\hat{p}_{0} &= -\hat{x}_{0}, \\
\hat{p}_{1} &= \hat{x}_{1} + zK_{1},
\end{align*}
\]

provides the following commutation relations:

\[
\begin{align*}
[J, \hat{p}_{0}] &= e_{ij} \hat{p}_{j}, \\
[J, K_{1}] &= e_{ij} K_{j}, \\
[J, \hat{p}_{0}] &= 0, \\
[\hat{p}_{1}, K_{1}] &= -\delta_{ij} \hat{p}_{0}, \\
[\hat{p}_{0}, \hat{p}_{1}] &= -zK_{1}, \\
[\hat{p}_{1}, \hat{p}_{2}] &= z^{2} J
\end{align*}
\]

that can directly be related to the initial Lie algebra (2). Consequently, whenever \(z\) is a real deformation parameter, the commutators (35) that do not depend on \(\omega\) close the Lie algebra \(so(3,1)\) for the three cases. Hence we obtain the dS spacetime as the homogeneous space

\[
dS^{2+1} \equiv \frac{\langle J, K, \hat{p}_{0} \rangle}{\langle J, K \rangle} = SO(3,1)/SO(2,1),
\]

such that the deformation parameter now plays the role of the (negative) curvature equal to \(-z^{2}\).

We stress that the connection between \(M_{z}^{2+1}\) and the dS space was so established in \([29]\) and further developed in \([30]\), so that the expressions (35) generalize such a link for the noncommutative (A)dS cases as well.

### 3.2 Noncommutative Spaces of Worldlines: Linear Relations

A similar procedure suggests that the corresponding noncommutative spaces of worldlines arise within the Drinfel'd-double through the commutators of \(\hat{x}\) and \(\hat{\xi}\) (dual to \(P\) and \(K\)); these are

\[
\begin{align*}
[\hat{x}_{0}, \hat{x}_{1}] &= -z\hat{x}_{1}, \\
[\hat{x}_{1}, \hat{x}_{2}] &= 0,
\end{align*}
\]

which are trivially independent of \(z\) and \(\omega\).
The adjoint action on the quantum coordinates $\hat{x}, \hat{\xi}$ of the isotropy subgroup of a worldline spanned by $J$ and $P_0$ gives the following nondeformed commutation rules:

$$[J, \hat{x}_i] = e_{ij} \hat{x}_j,$$
$$[J, \hat{\xi}_i] = e_{ij} \hat{\xi}_j,$$
$$[J, P_0] = 0,$$
$$[\hat{x}_i, \hat{\xi}_j] = 0,$$
$$[P_0, \hat{\xi}_i] = -\omega \hat{x}_i,$$
$$[\hat{\xi}_i, \hat{\xi}_j] = 0,$$  \hspace{1cm} (38)
$$[\hat{x}_1, \hat{\xi}_2] = 0,$$
$$[P_0, \hat{x}_1] = \hat{\xi}_1,$$

where the deformation parameter $z$ does not appear. To unveil this structure we rename the former generators as

$$J' = J,$$
$$P'_0 = -P_0,$$
$$P'_1 = \hat{\xi}_1,$$
$$K'_1 = \hat{x}_1,$$  \hspace{1cm} (39)

and from (38) we obtain the commutation relations

$$[J', P'_1] = e_{ij} P'_j,$$
$$[J', K'_1] = e_{ij} K'_j,$$
$$[J', P'_0] = 0,$$
$$[P'_1, K'_1] = 0,$$
$$[P'_0, K'_1] = 0,$$
$$[P'_0, K'_2] = 0,$$
$$[P'_1, K'_2] = 0,$$
$$[P'_1, P'_2] = \omega K'_1,$$
$$[P'_2, P'_2] = 0.$$

Surprisingly enough, these relations define just the Newtonian Lie algebras coming from the nonrelativistic limit $c \to \infty$ of the three Lorentzian Lie algebras (2), keeping the constant curvature $\omega$. Namely, the relations (40) close the oscillating Newton–Hooke, Galilei, and expanding Newton–Hooke algebras [19, 53, 63, 69] according to $\omega >, =, < 0$, respectively. This fact is consistent with the known result that establishes that each of the nonrelativistic Newtonian spaces of constant curvature $\omega$ can be obtained from the corresponding relativistic one through a contraction around a time-like line. Therefore, the classical (nondeformed) picture is preserved for worldlines.

Summing up, the first-order deformation of $so_\omega(2,2)$ characterized by the chosen $r$-matrix (26) conveys noncommutativity on the spacetime (33) but commutativity on the space of worldlines (37). Furthermore, space isotropy is ensured in both cases as the corresponding commutation relations do not involve the quantum rotation coordinate $\theta$.

4. A Poisson–Lie Structure on the (Anti-)de Sitter Groups

So far we have studied the first-order quantum (A)dS deformation. However, the obtention of the complete (in all orders in $z$ and in the generators) deformation of a semisimple group in terms of local coordinates is, in general, a very involved task. A way to study the noncommutative structures is to compute the Poisson–Lie brackets (derived from (26)) for the commutative coordinates and next to analyse their possible noncommutative version.

In particular, let us consider the $4 \times 4$ matrix element of the group $SO_\omega(2,2)$ obtained through the following product written under the representation (12):

$$T = \exp(x_0 P_0) \exp(x_1 P_1) \exp(x_2 P_2) \exp(\xi_1 K_1) \cdot \exp(\xi_2 K_2) \exp(\theta),$$  \hspace{1cm} (41)

where the group coordinates are commutative ones. Left- and right-invariant vector fields, $Y^L$ and $Y^R$, of $SO_\omega(2,2)$ deduced from (41) are displayed in Table 2. Notice that such expressions hold for any value of the curvature $\omega$. In the Poincaré case with $\omega = 0$, the vector fields, coming from the smooth contraction limit $\rho \to 0$, are rather simplified as shown in Table 3.

The Poisson–Lie brackets that close the algebra of smooth functions on the (A)dS groups, $Fun(SO_\omega(2,2))$ (r.h.s. of the diagram (1)), associated to an $r$-matrix $r = r_{ij} Y_j \otimes Y_i$ come from the Sklyanin bracket defined by [70]

$$\{f, g\} = r^{ij} \left( Y^L_i f Y^L_j g - Y^R_i f Y^R_j g \right),$$
$$f, g \in Fun(SO_\omega(2,2)).$$  \hspace{1cm} (42)

Thus by substituting the vector fields of Table 2 and the classical $r$-matrix (26) in (42) we obtain the Poisson–Lie brackets between the six commutative group coordinates $\{\theta, x_\mu, \xi_\mu\}$ which are split in the following three sets:

(i) those involving spacetime $x_\mu$ group coordinates,

$$\{x_0, x_1\} = -\frac{\tanh \rho x_1}{\rho \cosh^2 \rho x_2},$$
$$\{x_0, x_2\} = -\frac{\tanh \rho x_2}{\rho},$$
$$\{x_1, x_2\} = 0,$$  \hspace{1cm} (43)
### Left-invariant vector fields

<table>
<thead>
<tr>
<th>Expression</th>
<th>Formula</th>
</tr>
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</table>
| \( Y_{R}^{1} \) | \[
\frac{\cosh \rho \xi_{1}}{\cosh \rho \xi_{1}} \frac{\partial}{\partial \rho} + \rho \sin \rho \xi_{2} \frac{\partial}{\partial \rho} \]
| \( Y_{R}^{2} \) | \[
\frac{\sinh \rho \xi_{2}}{\cosh \rho \xi_{2}} \frac{\partial}{\partial \rho} \]
| \( Y_{R}^{3} \) | \[
\frac{\cos \rho \xi_{0}}{\sinh \rho \xi_{0}} \frac{\partial}{\partial \rho} - \rho \sin \rho \xi_{2} \frac{\partial}{\partial \rho} \]

### Right-invariant vector fields

<table>
<thead>
<tr>
<th>Expression</th>
<th>Formula</th>
</tr>
</thead>
</table>
| \( Y_{L}^{1} \) | \[
\frac{\cosh \rho \xi_{1}}{\cosh \rho \xi_{1}} \frac{\partial}{\partial \rho} - \rho \sin \rho \xi_{2} \frac{\partial}{\partial \rho} \]
| \( Y_{L}^{2} \) | \[
\frac{\sinh \rho \xi_{2}}{\cosh \rho \xi_{2}} \frac{\partial}{\partial \rho} \]
| \( Y_{L}^{3} \) | \[
\frac{\cos \rho \xi_{0}}{\sinh \rho \xi_{0}} \frac{\partial}{\partial \rho} + \rho \sin \rho \xi_{2} \frac{\partial}{\partial \rho} \]

### Table 2: Left- and right-invariant (anti-)de Sitter vector fields with \( \omega = \rho^{2} = -\Lambda \).
(ii) those that comprise space $\mathbf{x}$ and boost $\xi$ coordinates (besides the above vanishing bracket),

$$
\{x_1, \xi_1\} = -\frac{z}{\cosh \rho x_1} B = \frac{\sinh \rho x_2 B - \sinh \xi_1 \cosh \xi_2}{\cosh \rho x_1 \cosh \rho x_2},
$$

$$
\{x_2, \xi_2\} = z \left( \frac{\sinh \rho x_1}{\cosh \rho x_2} B - \frac{\sinh \xi_1 \cosh \xi_2}{\cosh \rho x_1 \cosh \rho x_2} \right),
$$

$$
\{x_2, \xi_1\} = -z A,
$$

$$
\{\xi_1, \xi_2\} = z \rho \sinh \rho x_1 \left( C - \frac{\tanh \xi_2}{\cosh^2 \rho x_2} \right),
$$

where the functions $A$, $B$, and $C$ are

$$
A = \frac{\sinh \rho x_1 \sinh \rho x_2 + \cosh \rho x_1 \sinh \xi_1 \tanh \xi_2}{\cosh \rho x_2},
$$

$$
B = \frac{\sinh \rho x_1 \tanh \rho x_2 \sinh \xi_1 + \sinh \rho x_2 \sinh \xi_2}{\cosh \rho x_2 \cosh \xi_2},
$$

$$
C = \frac{\sinh \rho x_1 \tanh \rho x_2 \sinh \xi_1 + \cosh \rho x_1 \sinh \xi_2}{\cosh \rho x_1 \cosh \rho x_2}.
$$

Notice that the commutators (30) are recovered from (43)–(46) by taking the first-order in the group coordinates.

We remark that any other choice for the matrix element of $SO_{\varepsilon}(2, 2)$ would lead to another set of vector fields formally different from those written in Table 2 and, therefore, it would give rise to Poisson–Lie brackets different from (43)–(46). However, by construction, all of these possible vector fields and Poisson–Lie structures are equivalent by means of changes of basis involving the group coordinates.

5. Noncommutative (Anti-)de Sitter Spaces

In general, the simplest way to quantize Poisson–Lie structures [5, 70] consists in the usual Weyl substitution of the initial Poisson brackets between commutative coordinates by commutators between noncommutative coordinates. Several quantum deformations of nonsemisimple groups have been constructed by applying this procedure; among them we underline the $\kappa$-Poincaré group [15–18], for which the full set of commutation rules are linear in the deformation parameter. Nevertheless, we stress that a quantum group does not always coincide with the Weyl quantization of their underlying Poisson–Lie brackets, specially when dealing with semisimple groups as the (A)dS ones, since ordering problems often appear during the quantization procedure.
In our case, the Poisson–Lie brackets (43)–(46) are the commutative counterpart of the full noncommutative quantum (A)dS groups $\text{Fun}_\omega(\text{SO}_n(2,1))$. Thus if we write a generic Poisson–Lie bracket as
\[
\{y^i, y^j\} = zf(y^1, \ldots, y^6),
\]
its noncommutative version would read
\[
\{\hat{y}^i, \hat{y}^j\} = zf(\hat{y}^1, \ldots, \hat{y}^6) + o(z^2),
\]
whose first-order in all $\hat{y}^k$ and $z$ is given by (30), while the $o(z^2)$ terms come from the reordering of the quantum coordinates $\hat{y}^k$. By following this point of view, we will analyse the generalization of the first-order noncommutative spaces presented in Section 3 to higher orders in the quantum coordinates and up to second-order in $z$.

5.1. Noncommutative Spacetimes. The first set of Poisson–Lie brackets (43) allows us to introduce the defining commutation relations of the $(2 + 1)$D noncommutative (A)dS spacetimes; namely,
\[
[\hat{x}_0, \hat{x}_1] = -z \frac{\tanh \rho \hat{x}_1}{\rho} + o(z^2)
\]
\[= -z \hat{x}_1 + \frac{1}{3} z \omega \hat{x}_1^3 + z \omega \hat{x}_1^2 \hat{x}_2^2 + o(z^2),
\]
\[
[\hat{x}_0, \hat{x}_2] = -z \frac{\tanh \rho \hat{x}_2}{\rho} + o(z^2)
\]
\[= -z \hat{x}_2 + \frac{1}{3} z \omega \hat{x}_2^3 + o(z^2),
\]
\[
[\hat{x}_1, \hat{x}_2] = 0 + o(z^2).
\]
These expressions demonstrate how the underlying first-order $\mathbf{M}^{2+1}_\omega$ (33) for the (A)dS groups is now generalized with an explicit dependence on the curvature $\omega$, in such a way that three different cases appear. Furthermore, space isotropy is preserved in the quantum case since $\tilde{\theta}$ is again absent (as well as the quantum boost coordinates $\tilde{\xi}$).

It is worth mentioning that the asymmetric form of (49) could be expected from the beginning (see, e.g., the classical metric (17)) as we are dealing with local quantum coordinates. However, if we consider noncommutative ambient (Weierstrass) coordinates $(\hat{s}_i, \hat{s}_j)$ defined in terms of the former ones $\hat{x}_m$ by the same formal relations (16) and subjected to the constraint (13), we obtain the noncommutative spacetimes written in a fully symmetric way as a quadratic algebra:
\[
[\hat{s}_0, \hat{s}_1] = -z \hat{s}_1 \hat{s}_0 + o(z^2),
\]
\[= 0 + o(z^2),
\]
\[= z \omega \hat{s}_0 \hat{s}_1 + o(z^2),
\]
\[
[\hat{s}_3, \hat{s}_1] = z \omega \hat{s}_0 \hat{s}_1 + o(z^2).
\]
These expressions are clearly invariant under the permutation $\hat{s}_1 \leftrightarrow \hat{s}_2$. The two first relations in (50) are just $\mathbf{M}^{2+1}_\omega$, since $\hat{s}_3 \rightarrow 1$ when $\omega \rightarrow 0$.

5.2. Noncommutative Spaces of Worldlines. Likewise, a first insight into the noncommutative (A)dS and Minkowskian spaces of time-like lines can be performed by starting with the Poisson–Lie brackets (44) among space $x$ and boost $\xi$ group coordinates.

Let us consider firstly the quantum Poincaré group with $\omega = 0$. In this case, the expressions (44) are rather simplified. Their corresponding quantum deformation reads
\[
[\hat{x}_1, \hat{\xi}_1] = z \left(1 - \frac{\cosh \hat{\xi}_1}{\cosh \hat{\xi}_2}\right),
\]
\[
[\hat{x}_2, \hat{\xi}_2] = z \left(\cosh \hat{\xi}_1 - \cosh \hat{\xi}_2\right),
\]
\[
[\hat{x}_1, \hat{\xi}_2] = -z \sinh \hat{\xi}_1 \sinh \hat{\xi}_2, \tag{51}
\]
\[
[\hat{x}_2, \hat{\xi}_1] = -z \sinh \hat{\xi}_1 \tanh \hat{\xi}_2,
\]
\[
[\hat{x}_1, \hat{x}_2] = 0,
\]
\[
[\hat{\xi}_1, \hat{\xi}_2] = 0,
\]
which determine the complete (in all orders in $z$, $\hat{x}$, and $\hat{\xi}$) noncommutative Minkowskian space of worldlines $\mathbf{L}_{2+1}^{\omega = 0}$. Hence the commutativity of the first-order relations $[\hat{x}_1, \hat{x}_2]$ is lost (see (37)). It is worth mentioning that $[\hat{\xi}_1, \hat{\xi}_2] = 0$ ensures the self-consistency of the remaining commutators as no ordering problems appear. Moreover, this condition means that the 2D velocity space remains nondeformed (commutative).

On the contrary, in the (A)dS cases with $\omega \neq 0$ the brackets (44) are rather involved, again asymmetric, and $\hat{\xi}_1, \hat{\xi}_2$ no longer commute. As in the classical case, we can consider the noncommutative ambient (Plücker) coordinates $(\hat{\eta}_3, \hat{\eta}_4, \hat{\eta}_5)$ formally defined by (23), but now with noncommutative entries $\hat{\xi}$ and $\hat{\eta}$. Then the noncommutative (A)dS spaces of worldlines are given by the following quadratic relations:
\[
[\hat{y}_1, \hat{y}_2] = -z \left(\hat{\eta}_3 - \left(\hat{\eta}_3^2 - \omega \hat{y}_3^2\right)\right) \hat{y}_3 + o(z^2),
\]
\[
[\hat{y}_3, \hat{\eta}_3] = 0 + o(z^2),
\]
\[
[\hat{\eta}_1, \hat{\eta}_2] = -z \omega \left(\hat{\eta}_3 - \left(\hat{\eta}_3^2 - \omega \hat{y}_3^2\right)\right) \frac{\hat{\eta}_3 - 1}{\hat{\eta}_3} \hat{y}_3
\]
\[+ o(z^2),
\]
\[
[\hat{\eta}_3, \hat{\eta}_1] = z \omega \left(\hat{\eta}_3 \hat{\eta}_1 \hat{y}_3 + \hat{y}_1 \left(\hat{\eta}_3^2 - \omega \hat{y}_3^2\right) \frac{\hat{\eta}_3 - 1}{\hat{\eta}_3}\right)
\]
\[+ o(z^2),
\]
which are invariant under the map defined by
\[
[\eta_{i}, \eta_{j}] = z \left( \omega e_{ij} \eta_{j} \eta_{3} - \eta_{i} \left( \frac{\eta_{3} - 1}{\eta_{3}} \right) \right) + o(z^2),
\]
\[
[\eta_{i}, \eta_{j}] = \omega e_{ij} (\eta_{3} - 1) - \eta_{i} \left( \frac{\eta_{3} - 1}{\eta_{3}} \right),
\]
\[
[\eta_{i}, \eta_{j}] = 0,
\]
\[
[\eta_{i}, \eta_{j}] = 0,
\]
\[
[\eta_{3}, \eta_{3}] = z \delta_{ij} \eta_{i} \eta_{3} (\eta_{3} - 1).\]

The commutativity of the 2D velocity space in \[\text{LM}_{z}^{2\times 2}\] now comes from the fact that the commutators involving the "momentum-like" coordinates \((\eta_{i}, \eta_{j})\) vanish; note that they only depend on \(\xi\), which commute in this case. On the contrary, the "position-like" ones \((\tilde{\eta}_{i}, \tilde{\eta}_{j})\) do not commute; they depend on both \(\xi\) and \(\bar{\xi}\) (see (24)). We stress that this quantum Poincaré group property is in full agreement with the study developed in [71, 72] by working with the (dual) quantum algebra. In these works it is shown how the \(\kappa\)-deformed Poincaré boost transformations close a group as in the nondeformed case, and the additivity of the boost parameter for transformations along the same direction is also preserved. Therefore, the relations (52) indicate that such properties may be either lost or somewhat modified in the quantum \((A)dS\) groups.

### 6. Quantum (Anti-)de Sitter Algebras

In this section we firstly review the Hopf algebra structure and the associated invariants of the quantum \((A)dS\) algebras that quantize the cocommutators (27), commutators (2), and Casimirs (9). These results are presented in the kinematical basis in which they were formerly obtained [19], and the contraction \(\omega = 0\) gives the \(\kappa\)-Poincaré written in the form deduced in [13]. We also point out some remarks concerning the connection between these structures and quantum gravity that has been introduced in [38]. Secondly, we obtain a new basis through a nonlinear map for these quantum algebras in such a manner that the \(\kappa\)-Poincaré algebra is recovered in the so-called bicrossproduct basis [8, 16]. This change of basis, at the level of the quantum algebra, is the dual counterpart to a change of noncommutative coordinates on the quantum group.

#### 6.1. "Symmetrical" Basis

The Drinfel'd–Jimbo quantum deformation of \(\text{so}(4, \mathbb{C})\) was obtained in [11] by considering two copies of the quantum \(\text{su}(2)\) algebra [3] and applying the prescription \(U_z(\text{so}(4, \mathbb{C})) = U_z(\text{su}(2)) \oplus U_z(\text{su}(2))\). From this result, a further analysis of real forms together with a contraction scheme led to quantum deformations of the family of \((2 + 1)\)D kinematical algebras [19, 68] which included, among others, the \(\kappa\)-deformation of the three relativistic algebras (2) with underlying Lie bialgebra (27) that we denote here by \(U_z(\text{so}_{\kappa}(2, 2))\). The Hopf structure of \(U_z(\text{so}_{\kappa}(2, 2))\) is characterized by the following coproduct and commutation relations [19]:

\[
\Delta(P_{0}) = 1 \otimes P_{0} + P_{0} \otimes 1,
\]
\[
\Delta(J) = 1 \otimes J + J \otimes 1,
\]
\[
\Delta(P_{i}) = e^{-(z/2)P_{0}} \cosh \left( \frac{z}{2} \rho J \right) \otimes P_{i} + P_{i} \otimes e^{-(z/2)P_{0}} \cosh \left( \frac{z}{2} \rho J \right),
\]
\[
\Delta(e_{ij}K_{j}) = e^{-(z/2)P_{0}} \sinh \left( \frac{z}{2} \rho J \right) \otimes e_{ij}K_{j} - e_{ij}K_{j} \otimes e^{-(z/2)P_{0}} \sinh \left( \frac{z}{2} \rho J \right),
\]
\[
\Delta(K_{i}) = e^{-(z/2)P_{0}} \cosh \left( \frac{z}{2} \rho J \right) \otimes K_{i} + K_{i} \otimes e^{-(z/2)P_{0}} \cosh \left( \frac{z}{2} \rho J \right),
\]
\[
\Delta(e_{ij}P_{j}) = e^{-(z/2)P_{0}} \sinh \left( \frac{z}{2} \rho J \right) \otimes e_{ij}P_{j} + e_{ij}P_{j} \otimes e^{-(z/2)P_{0}} \sinh \left( \frac{z}{2} \rho J \right).
\]
\[ [J, P_i] = e_i P_j, \]
\[ [J, K_i] = e_i K_j, \]
\[ [J, P_0] = 0, \]
\[ [P_i, K_j] = -\delta_{ij} \frac{\sinh(zP_0)}{z} \cosh(zp^i), \]
\[ [P_0, K_i] = -P_i, \]
\[ [P_0, P_i] = \omega K_i, \]
\[ [P_1, P_2] = -\omega \cosh(zP_0) \frac{\sinh(zp^i)}{zp^i}, \]
\[ [K_1, K_2] = -\cosh(zP_0) \frac{\sinh(zp^i)}{zp^i}. \]

Counting and antipode maps can directly be derived from the Hopf algebra axioms. The deformation of the two Casimir invariants (9) turns out to be

\[ \mathcal{C} = 4 \cos(zp) \left\{ \sinh^2\left(\frac{z}{2} P_0\right) - \cosh^2\left(\frac{z}{2} p^i\right) \right\} \]
\[ + \frac{\sinh^2\left(\frac{z}{2} \rho^i\right)}{z^2} \cosh^2\left(\frac{z}{2} p^i\right) - \sin\left(\frac{zp}{2}\right) \frac{p^2}{z^2} \]
\[ + \omega K_i^2 \right\}, \]
\[ \mathcal{W} = \sinh^2\left(\frac{z}{2} P_0\right) \cosh^2\left(\frac{z}{2} p^i\right) - \frac{\sin(zp)}{zp} (p^i) \]
\[ + \frac{\sin(zp)}{zp} (K_1 P_2 - K_2 P_1). \]
(\sqrt{\omega} = \rho \text{ plays the role of the usual Inönü–Wigner contraction parameter}). This map is associated with the \( \mathbb{Z}_2 \)-grading of \( U_\omega^0(\mathfrak{so}(2, 2)) \) given by the composition of the deformed parity and time-reversal (32):

\[
\Pi_2 \Theta_2 : (P_0, P, K, J; z) \rightarrow (-P_0, -P, K, J; -z).
\]

By computing the coproduct and commutation relations for the new generators \( Y' \) from \( U_\omega(\mathfrak{so}(2, 2)) \) and then by applying the limit \( \sqrt{\omega} \to 0 \), one finds the \( \kappa \)-Poincaré algebra in terms of the transformed deformation parameter \( z' \). Therefore, if \( z' \) is now taken as the Planck length \( l_p \) and \( \omega \equiv -\Lambda > 0 \), the map (58) means that \( z = \sqrt{-\Lambda} l_p \), so that the contraction \( \sqrt{-\Lambda} \to 0 \) conveys the limit \( z \to 0 \) as well, leaving \( Z' \equiv l_p \) as the only fundamental scale in \( \kappa \)-Poincaré, in agreement with [38].

### 6.3. "Bicrossproduct-Type" Basis

So far, most of the applications of the \( \kappa \)-Poincaré algebra have been developed by working in the so-called bicrossproduct basis [16, 22], in which the Lorentz sector has nondeformed commutation rules. Thus it is natural to wonder about the existence of a nonzero curvature counterpart of such a basis. This can be achieved by means of the \( \omega \)-generalization of the invertible nonlinear map introduced for \( \kappa \)-Poincaré in [16]

\[
\begin{align*}
\bar{P}_0 &= P_0, \\
\bar{J} &= J, \\
\bar{P}_i &= e^{-(z/2)\rho_p} \left\{ \cosh \left( \frac{z}{2} \rho J \right) P_i - \rho \sinh \left( \frac{z}{2} \rho J \right) \epsilon_{ij} K_j \right\}, \\
\bar{K}_i &= e^{-(z/2)\rho_p} \left\{ \cosh \left( \frac{z}{2} \rho J \right) K_i + \frac{\sinh \left( (z/2) \rho \right)}{\rho} \epsilon_{ij} P_j \right\}.
\end{align*}
\]

This transformation can be written as the following matrix transformation of \( P \) and \( K \) depending on functions of the generators of the isotropy subgroup of a worldline:

\[
\begin{pmatrix}
\bar{P}_1 \\
\bar{P}_2 \\
\bar{K}_1 \\
\bar{K}_2
\end{pmatrix}
= \exp \left\{ -\frac{z}{2} P_0 \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\right\}
\cdot
\exp \left\{ -\frac{z}{2} \begin{pmatrix}
0 & 0 & 0 & w \\
0 & 0 & -w & 0 \\
0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0
\end{pmatrix}
\right\}
\cdot
\begin{pmatrix}
P_1 \\
P_2 \\
K_1 \\
K_2
\end{pmatrix}. \tag{61}
\]

The transformed coproduct and commutation rules of \( U_\omega(\mathfrak{so}(2, 2)) \) in this new basis turn out to be

\[
\begin{align*}
\Delta(\bar{P}_0) &= 1 \otimes \bar{P}_0 + \bar{P}_0 \otimes 1, \\
\Delta(\bar{J}) &= 1 \otimes \bar{J} + \bar{J} \otimes 1, \\
\Delta(\bar{P}_i) &= e^{-z \rho_p} \bar{P}_i + \bar{P}_i \otimes \sinh (z \rho J) - \rho \epsilon_{ij} \bar{K}_j \\
&\otimes \sinh (z \rho J), \\
\Delta(\bar{K}_i) &= e^{-z \rho_p} \bar{K}_i + \bar{K}_i \otimes \cosh (z \rho J) + \epsilon_{ij} \bar{P}_j \\
&\otimes \frac{\sinh (z \rho J)}{\rho}, \\
[\bar{J}, \bar{P}_i] &= \epsilon_{ij} \bar{P}_j, \\
[\bar{J}, \bar{K}_i] &= \epsilon_{ij} \bar{K}_j, \\
[\bar{J}, \bar{P}_0] &= 0, \\
[\bar{P}_0, \bar{K}_i] &= -\bar{P}_i, \\
[\bar{P}_0, \bar{P}_i] &= \omega \bar{K}_i, \\
[\bar{P}_i, \bar{P}_j] &= -\omega \frac{\sinh (2z \rho J)}{2z}, \\
[\bar{K}_i, \bar{K}_j] &= -\frac{\sinh (2z \rho J)}{2z}, \\
[\bar{P}_i, \bar{K}_j] &= \delta_{ij} \left\{ \frac{e^{-z \rho_p} - \cosh (2z \rho J)}{2z} \\
- \frac{\tan (z \rho)}{2z} \left( \bar{P}_j \bar{P}_i + \omega \bar{K}_j^2 \right) \right\} + \frac{\tan (z \rho)}{\rho} \left( \bar{P}_j \bar{P}_i \\
+ \omega \bar{K}_i \bar{K}_j \right). \tag{62}
\end{align*}
\]

Therefore, the Lorentz sector remains deformed in the quantum (A)dS algebras with \( \omega \neq 0 \), while the contraction \( \omega = 0 \) (\( \rho \to 0 \)) produces the \( \kappa \)-Poincaré algebra in the bicrossproduct basis, in which the only deformed commutation rules are \([\bar{P}_i, \bar{K}_j]\). However, although the Lorentz sector in \( \kappa \)-Poincaré is nondeformed, the quantum deformation is still kept in the coproduct for the boost generators (62). Note also that this new coproduct is not invariant under the map \( \sigma \ast \mathcal{S} \).

The corresponding deformed Casimirs are obtained from (57) and read

\[
\begin{align*}
\mathcal{C} &= 4 \cos (z \rho) \left\{ \frac{\sinh^2 \left( \frac{z}{2} \rho_p \right)}{z^2} \cosh^2 \left( \frac{z}{2} \rho J \right) \\
+ \frac{\sinh^2 \left( \frac{z}{2} \rho J \right)}{z^2} \cosh^2 \left( \frac{z}{2} \rho_p \right) \right\} - \frac{\sin (z \rho)}{2z}
\end{align*}
\]
turn out to be determined through quadratic commutation and (23) for the ("local") parametrizations of such spaces. and spaces of worldlines in terms of ambient ("global") have allowed us to write both noncommutative spacetimes appropriate treatment of the classical (nondeformed) structures are different from the cases they are related to phase spaces (see [90–93]).

It is worth stressing that the connection between the Poisson–Lie group approach presented here and the role that classical r-matrices and Drinfel’d-doubles play in the context of 2 + 1 quantum gravity [76–84] has been studied in detail in the works [85–89]. Also, the deformed Casimir operators (57) (or (64)) can be used to provide modified dispersion relations, which should be related to those appearing in several phenomenological approaches to quantum gravity (see [90–93]).

Some comments on other possible quantum deformations of the (A)dS algebras are in order. Since any possible quantum deformation of the (A)dS algebras has to come from a classical r-matrix, a complete classification of the latter would be certainly useful in order to obtain and analyse other physically interesting quantum (A)dS groups (for each of them, the vector fields displayed in Table 2 would give rise to the associated Poisson noncommutative spaces). In this respect, the full classification of classical r-matrices for the (3 + 1)D Poincaré Lie algebra can be found in [94]. For the (2 + 1)D (A)dS algebras a similar result has been recently given in [95] (see also [96]).

On the other hand, the generalization of the (2 + 1)D κ-(A)dS algebras and groups to the (3 + 1)D case can be obtained by generalizing the classical r-matrix (26) to (see [68])

\[ r = z (K_1 \wedge P_1 + K_2 \wedge P_2 + K_3 \wedge P_3) + z \sqrt{\omega} J_1 \wedge J_2, \]

which include a term \( J_1 \wedge J_2 \) coming from the rotation sector. This term does not appear either in the (3 + 1)D \( \kappa \)-Poincaré algebra (with \( \omega = 0 \)) or in the (2 + 1)D \( \kappa \)-(A)dS algebras. A twisted version of (66) with a second deformation parameter \( \theta \) was considered in [97] by imposing some physical requirements, and the very same classical r-matrix has been derived in [98] from a Drinfel’d-double approach; namely,

\[ r = z (K_1 \wedge P_1 + K_2 \wedge P_2 + K_3 \wedge P_3) + z \sqrt{\omega} J_1 \wedge J_2 + \theta J_3 \wedge P_0. \]

The corresponding Poisson–Hopf algebra has been recently constructed in [99], so obtaining the (3 + 1)D Poisson version of the coproduct (62), commutation relations (63), and Casimirs (64). The associated (3 + 1)D noncommutative spacetime, generalizing (49), is currently under investigation.

Finally, we recall that other different quantum (A)dS deformations have been obtained by working in a conformal basis instead of a pure kinematical one, for instance, so(3,2) [100, 101] and so(4,2) [47, 102–104], and the Drinfel’d–Jimbo quantum AdS space at roots of unity has been worked out in [105]. Also, other fuzzy [106, 107] and covariant [44] noncommutative (A)dS spacetimes have also been constructed.

### 7. Concluding Remarks

We have presented a unified and global study of the \( \kappa \)-deformation of the (A)dS and Poincaré algebras and groups in 2 + 1 dimensions by making use of an explicit contraction parameter \( \omega \) that corresponds to the curvature/cosmological constant of the underlying classical spacetimes. We remark that the limit \( \omega \to 0 \) is always well defined in all the expressions, thus providing a straightforward Poincaré/Minkowskian counterpart of all the results here presented.

At the quantum algebra level, we have introduced a new basis (60) for the quantum (A)dS algebras, which is the analogous of the \( \kappa \)-Poincaré bicrossproduct basis. As far as the (dual) quantum groups are concerned, the results cover the noncommutative (A)dS spacetimes (49) up to second-order in the deformation parameter, thus generalizing the \( \kappa \)-Minkowskian spacetime (33) which turns out to be their common first-order seed. Furthermore, we have presented the first approach, to the best of our knowledge, to noncommutative spaces of worldlines. For the three relativistic cases they are related to phase spaces \( (\mathbf{x}, \mathbf{\xi}) \leftrightarrow (P, K) \), which are different from the \( \kappa \)-Poincaré phase spaces proposed in [29, 30] (see also [75]). We also remark that an appropriate treatment of the classical (nondeformed) structures have allowed us to write both noncommutative spacetimes and spaces of worldlines in terms of ambient ("global") coordinates, starting with the particular expressions (16) and (23) for the ("local") parametrizations of such spaces. In such ambient coordinates, the noncommutative spaces turn out to be determined through quadratic commutation relations (50) and (52). Moreover, they are shown to be symmetric with respect to some maps that generalize the \( P_1 \leftrightarrow P_2 \) and \( K_1 \leftrightarrow K_2 \) invariance of the dual quantum algebras.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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