CHARGES IN THE EXTENDED BMS ALGEBRA: DEFINITIONS AND APPLICATIONS

BASED ON

R. Javdadinezhad, U. Kol, MP, to appear and

JHEP 1901(2019) 89

arxiv:1808.02987 [hep-th]

U. Kol and MP,

Phys. Rev. D100, 046019 (2019)

arXiv:1907.00990 [hep-th]

Phys. Rev. D101, 126009 (2020)

arXiv:2003.09054 [hep-th].

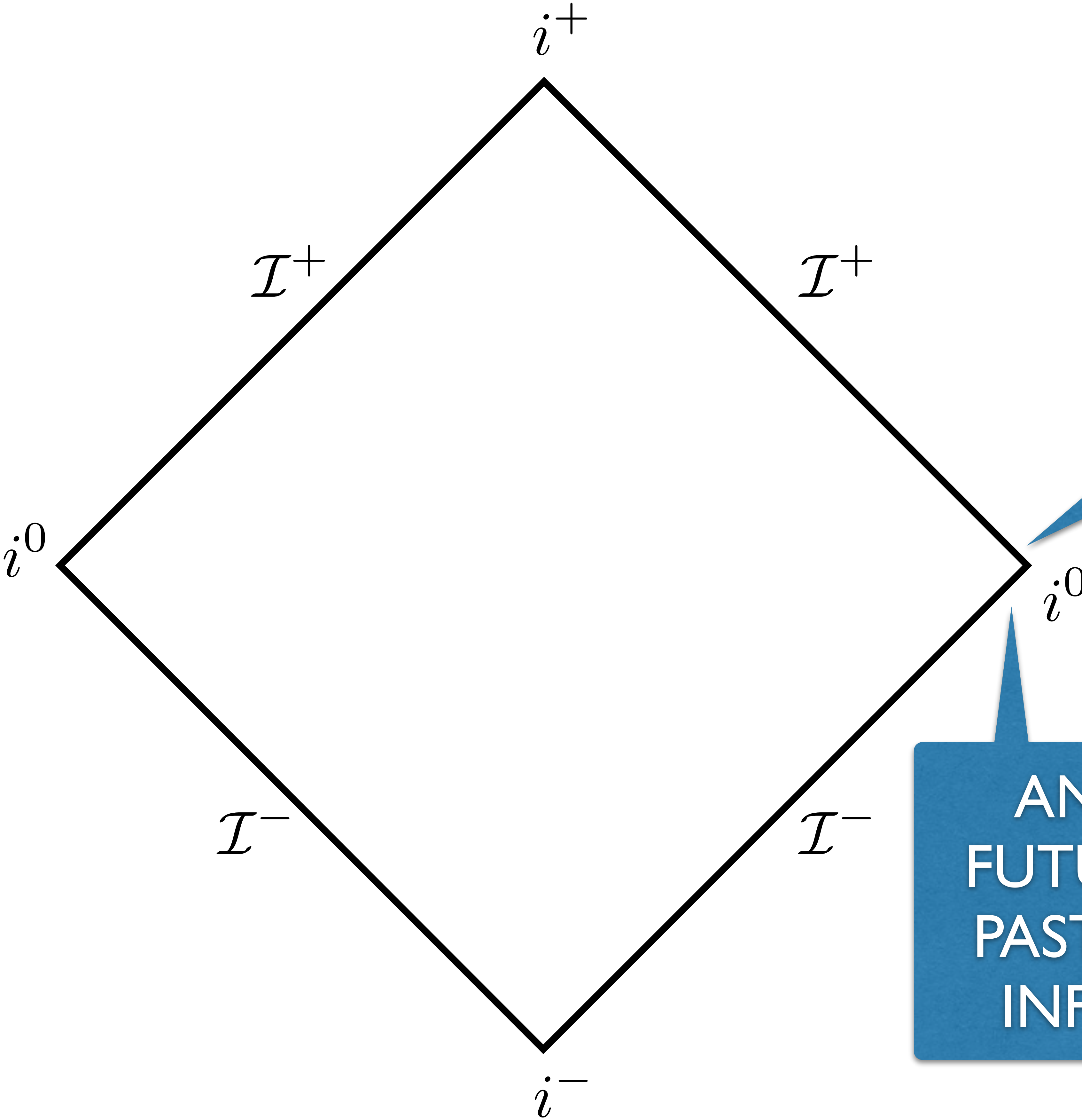
AND PREVIOUS WORK

R. Bousso, MP, CQG 34 (2017) n. 20, 204001

arxiv:1706.00436 [hep-th]

- BMS CHARGES, HARD AND SOFT BMS CHARGES
- BMS CHARGE CONSERVATION LAWS
- DUAL CHARGES
- DUAL GAUGE INVARIANCE?
- TAUB-NUT AS WU-YANG?
- A “BETTER LORENTZ TRANSFORMATION”
- CONSISTENCY OF THE NEW LORENTZ ALGEBRA

BMS CHARGES



CHARGES ARE DEFINED AT PAST OF FUTURE NULL INFINITY

AND AT FUTURE OF PAST NULL INFINITY

BMS CHARGES AT FUTURE INFINITY

$$ds^2 = -du^2 - 2dudr + \frac{2m}{r}du^2 + \frac{4r^2 dz dz^*}{(1+zz^*)^2} + rC_{zz}dz^2 + rC_{z^*z^*}dz^{*\,2} + \ldots$$

$$N_{zz} = \partial_u C_{zz}$$

BONDI NEWS

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BONDI NEWS

$$T(f) = \frac{1}{4\pi G}\int_{I^+_-} d^2z\,\gamma_{zz^*} f(z, z^*) m$$

BONDI MASS ASPECT

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BONDI NEWS

$$T(f) = \frac{1}{4\pi G}\int_{I^+_-} d^2z\,\gamma_{zz^*} f(z,z^*)m$$

BONDI MASS ASPECT

$$T(f) = T_s(f) + T_h(f)$$

$$T_h(f) = \frac{1}{4\pi G}\int_{I^+} dud^2z\,\gamma_{zz^*} f(z,z^*)T_{uu}$$

$$T_s(f) = \frac{1}{16\pi G}\int_{I^+} dud^2z\,\gamma^{zz^*} f(z,z^*)(D_{z^*}^2 N_{zz} + D_z^2 N_{z^*z^*})$$

BOUNDARY CONDITION

$$\lim_{u \to -\infty} C_{zz} = D_z^2 C(z, z^*)$$

BOUNDARY GRAVITON

ONE POLARIZATION ONLY: C(z,z*) IS <u>REAL</u>

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ONE POLARIZATION ONLY: C(z,z*) IS <u>REAL</u>

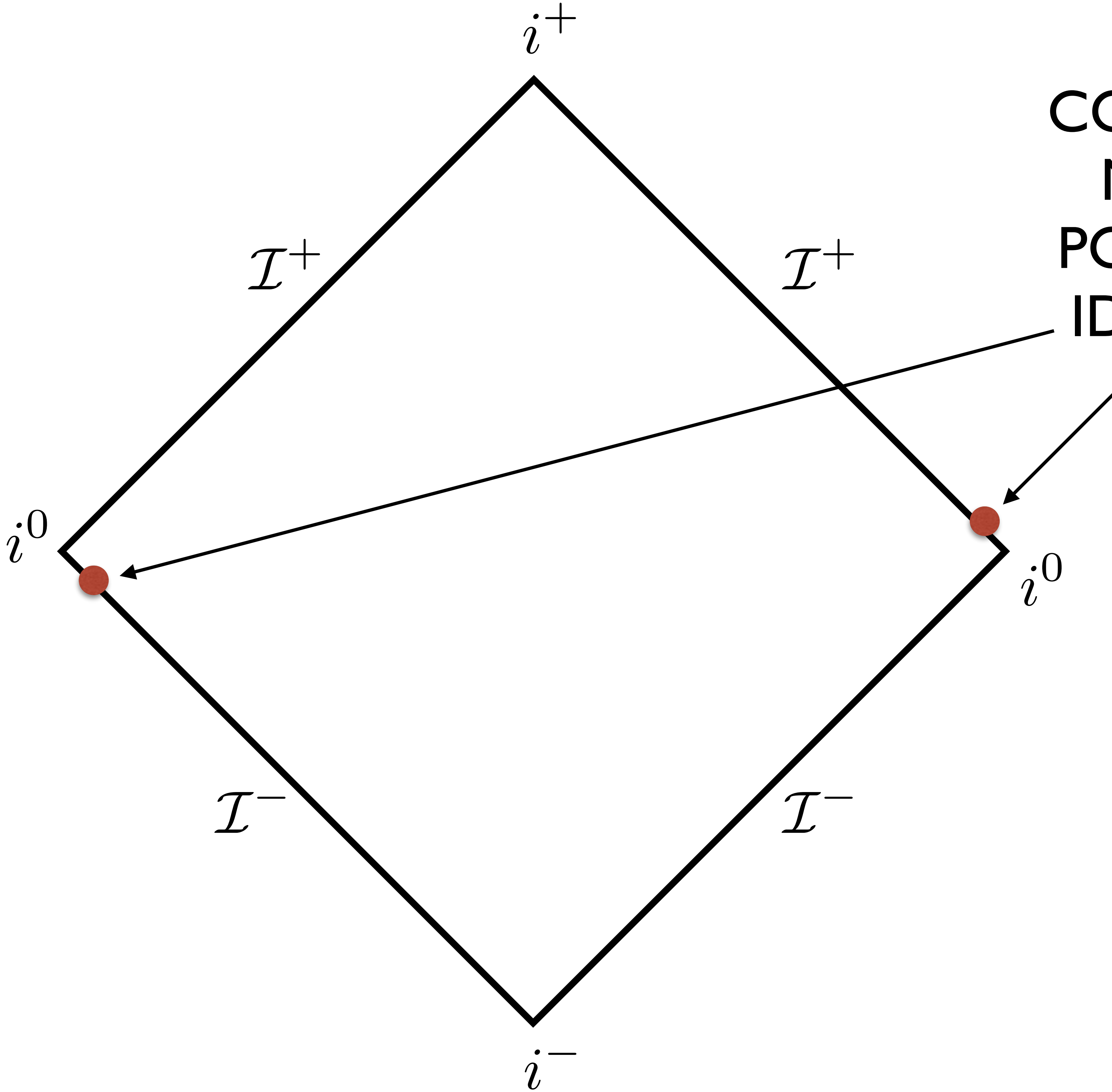
WITH THIS CHOICE SUPERTRANSLATIONS ACT BY LIE DERIVATIVES ON THE METRIC

$$\{T(f), C_{zz}\} = fN_{zz} - 2D_z^2 f, \qquad \{T(f), C\} = -2f$$

SO SUPERTRANSLATIONS ACT AS DIFFEOMORPHISMS: z DEPENDENT TRANSLATIONS IN RETARDED TIME u

$$u \to u + f(z, z^*)$$

BMS CHARGES CONSERVATION



CONFORMAL COMPACTIFICATION MAKES THE TWO POINTS CLOSE AND IDENTIFIES ANGLES ANTIPODALLY

$$\phi^- = \phi^+ + 2\pi$$

$$\theta^- = \pi - \theta^+$$

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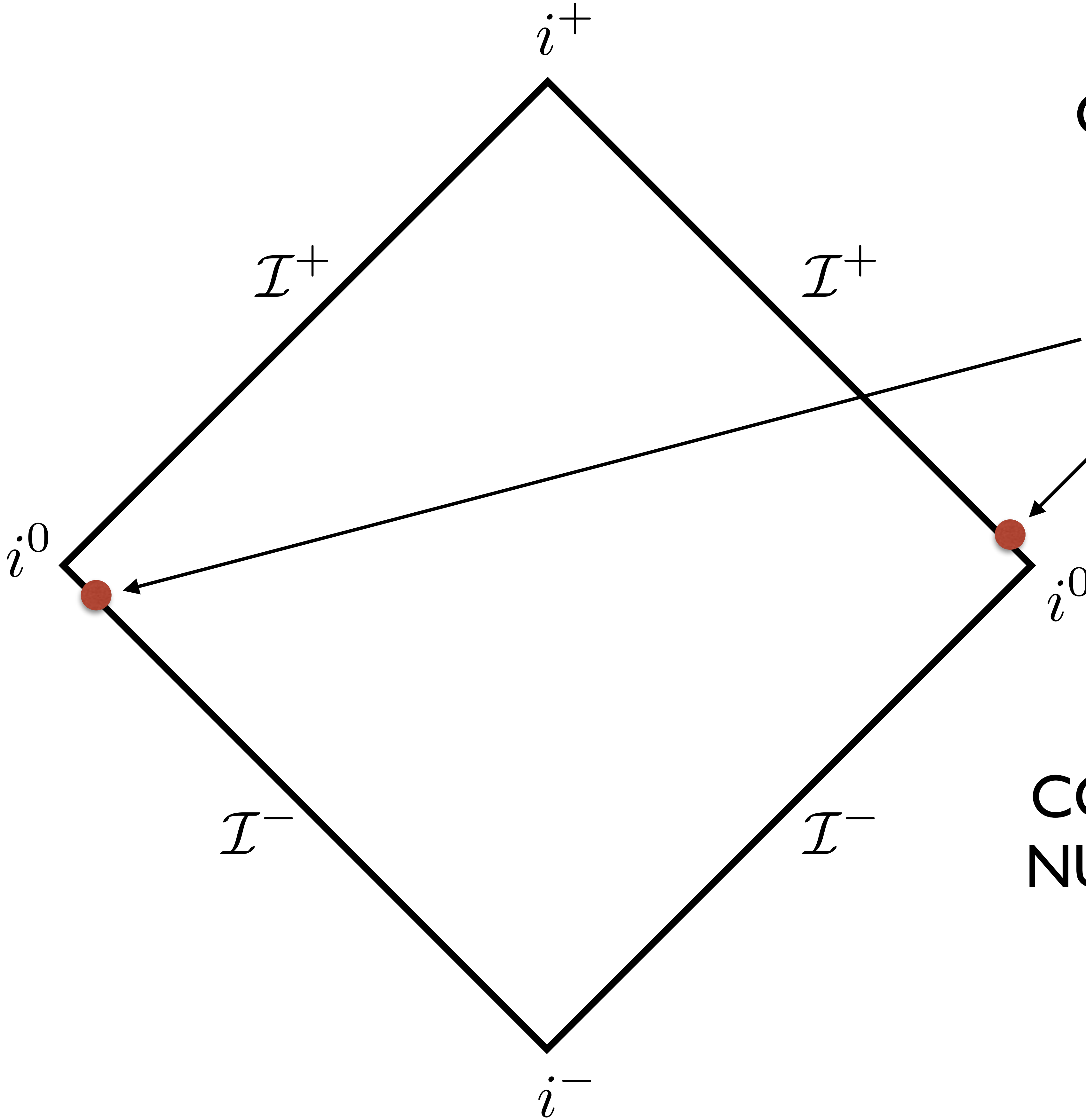

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CONTINUITY ALONG NULL GENERATOR OF BOUNDARY=BMS CHARGE CONSERVATION

THE BOUNDARY GRAVITON ALSO OBEYS A SIMPLE MATCHING CONDITION WHEN ANGLES AT PAST AND FUTURE NULL INFINITY ARE IDENTIFIED ANTIPODALLY

$$C(z, z^*) = C^-(w^*, w), \qquad z = w^*$$

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SEVERAL ARGUMENTS SUPPORT THIS MATCHING CONDITION

IN PARTICULAR, IT IS THE ONLY LORENTZ AND CPT INVARIANT BOUNDARY CONDITION, IT IS USED IN MOST GENERAL RELATIVITY COMPUTATIONS IN ASYMPTOTICALLY FLAT SPACETIME AND IT IS VALID TO ALL-ORDER PERTURBATIVE GRAVITY COMPUTATIONS

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HERE WE ASSUMED THAT

$$C = C^*$$

BUT A MORE GENERAL BOUNDARY CONDITION IS POSSIBLE

WE WANT TO STUDY IN PARTICULAR THE CASE

$$C = -C^*$$

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BMS SUPERTRANSLATIONS DO NOT PRESERVE THIS BOUNDARY CONDITION BUT

DUAL SUPERTRANSLATIONS DO

$$C(z, z^*) \to C(z, z^*) - 2f(z, z^*), \qquad f = -f^*$$

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$$C(z, z^*) \to C(z, z^*) - 2f(z, z^*), \qquad f = -f^*$$

THE GENERATOR OF DUAL SUPERTRANSLATIONS IS

$$M(f) = -\frac{i}{16\pi G} \int_{I+} du d^2 z \gamma^{zz^*} f(z, z^*)(D^2_{z^*} N_{zz} - D^2_z N_{z^* z^*})$$

DUAL SUPERTRANSLATIONS DO NOT ACT ON MATTER FIELDS SO THEY ARE NOT DIFFEOMORPHISMS

PROPERTIES OF DUAL SUPERTRANSLATIONS

- CHARGE CONSERVED BY IMPOSING ANTIPODAL MATCHING CONDITIONS
- ZERO MODE [f(z,z*)=constant] IS A TOPOLOGICAL INVARIANT (SIMILARLY TO THE MAGNETIC CHARGE)

$$\delta M(f) = \frac{i}{16\pi G}\int_{I^{+}_{-}} d^2 z \gamma^{zz^*} f(z,z^*)(D^2_{z^*}\delta C_{zz} - D^2_z \delta C_{z^*z^*}) = 0$$

GLOBALLY DEFINED ON 2-SPHERE

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GLOBALLY DEFINED ON 2-SPHERE

DUAL SUPERTRANSLATIONS ACT TRIVIALLY ON S-MATRIX ELEMENTS.

<u>CONSISTENT WITH IT BEING A GAUGE INVARIANCE</u>

LET US DO THIS LOGICAL JUMP AND ASSUME THAT IT IS A GAUGE INVARIANCE.

WHY NOT CHOOSE THE GAUGE

$\mathrm{Im}\ C=0$

AND PRETEND THAT DUAL SUPERTRANSLATIONS NEVER EXISTED?

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WHY NOT CHOOSE THE GAUGE

Im C=0

AND PRETEND THAT DUAL SUPERTRANSLATIONS NEVER EXISTED?

WE COULD HAVE ASKED THE SAME QUESTION IN THE ABELIAN HIGGS MODEL.

THERE, THE GAUGE CHOICE

$$\mathrm{Im}\,\phi = 0$$

CREATES A FAKE SINGULARITY FOR A.N.O. STRINGS, WHICH ARE INSTEAD REGULAR WHEN THE ASYMPTOTIC BEHAVIOR OF THE FIELDS IS

$$\lim_{r\to\infty} A_\theta(r,\theta) = n \qquad \lim_{r\to\infty} \phi(r,\theta) = ve^{in\theta}$$

LET'S USE THIS INSIGHT TO DEAL WITH A FAMOUSLY NASTY SOLUTION OF EINSTEIN'S EQUATIONS: THE TAUB-N.U.T. SPACE

$$
\begin{aligned}
ds^2 &= -f(r)(dt + 2l\cos\theta d\varphi)^2 + \frac{dr^2}{f(r)} + (r^2 + l^2)(d\theta^2 + \sin^2\theta d\varphi^2) \\
f(r) &= \frac{r^2 - 2mr - l^2}{r^2 + l^2}
\end{aligned}
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THERE IS A SINGULARITY AT $\theta = 0, \pi$

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REMOVED BY COORDINATE TRANSFORMATION

$$t = t_N - 2l\varphi, \quad 0 \leq \theta \leq \frac{\pi}{2}; \qquad t = t_S + 2l\varphi, \quad \frac{\pi}{2} \leq \theta \leq \pi$$

NEW METRIC DEFINED IN TWO PATCHES.
JOINED AT EQUATOR BY A DIFFEOMORPHISM

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PERIODICITY IN ANGLE IMPLIES CLOSED TIMELIKE CURVES

IF DUAL SUPERTRANSLATIONS ARE A GAUGE SYMMETRY WE HAVE AN ALTERNATIVE THAT AVOIDS CTCs AND SINGULARITIES

$$ds_N^2 = -f(r)\left(dt - 4l\sin^2\frac{\theta}{2}d\varphi\right)^2 + \frac{dr^2}{f(r)} + (r^2+l^2)(d\theta^2 + \sin^2\theta d\varphi^2)$$

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SAME COORDINATES EVERYWHERE BUT METRIC JOINED AT EQUATOR BY DUAL SUPERTRANSLATION

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ASYMPTOTIC METRIC IS

$$ds^2 = -du^2 - 2dudr + \frac{2m}{r}du^2 + \frac{4r^2dzdz^*}{(1+zz^*)^2} + rD_z^2Cdz^2 + rD_{z^*}^2C^*dz^{*\,2} + \ldots$$

WITH

$$C_N = -4il\log(1+zz^*), \qquad C_S = 8il\log(1+1/zz^*)$$

AT EQUATOR THE TWO METRICS ARE EQUIVALENT UP TO A DUAL SUPERTRANSLATION

$$C_S = C_N + 8il \log |z|$$

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BY ADDING AN IMAGINARY PART TO THE BOUNDARY GRAVITON AND THEN REMOVING IT BY GAUGE INVARIANCE WE GAINED SOMETHING: WE MADE TAUB-N.U.T. NONSINGULAR (AT LEAST ASYMPTOTICALLY)

THERE IS NO PERIODIC IDENTIFICATION OF TIME BECAUSE HERE SPACETIME COORDINATES ARE DEFINED GLOBALLY.

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NO CLOSED TIMELIKE CURVES IN EITHER TAUB OR N.U.T. REGIONS WHEN

$$m/l \leq \sqrt{5/27}$$

BACK TO BMS SUPERTRANSLATIONS

THE (REAL) BOUNDARY GRAVITON CAN BE EXPANDED IN SPHERICAL HARMONICS ON THE CELESTIAL SPHERE. THE BOUNDARY CONDITION THEN BECOMES

$$C^{+}_{lm} = C^{-}_{lm}$$

HERE FUTURE QUANTITIES DEFINED ON I+ CARRY THE SUPERSCRIPT (+) AND PAST QUANTITIES ON I- CARRY A (-)

THE SUPERTRANSLATION CHARGES CAN ALSO BE EXPANDED IN SPHERICAL HARMONICS.

CHARGE CONSERVATION THEN BECOMES

$$Q^{+}_{lm} = Q^{-}_{lm}$$

A CANONICAL TRANSFORMATION

DEFINE IT AS FOLLOWS

$$U Q^{+}_{s\,lm} U^{-1} = Q^{+}_{lm} \qquad U C^{+}_{lm} U^{-1} = C^{+}_{lm}$$

EXPLICITLY

$$U = \exp[-i \sum_{l=2}^{\infty} \sum_{m=-l}^{l} Q^{+}_{h\,lm} C^{+}_{lm}]$$

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DEFINE DRESSED VARIABLES BY THE SAME CANONICAL TRANSFORMATION

$$UN^+_{AB}U^{-1} \equiv \hat{N}^+_{AB}$$

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KEY PROPERTY: THEY COMMUTE WITH THE BMS CHARGES

$$[\hat{N}^{+}_{AB}, Q^{+}_{lm}] = U[N^{+}_{AB}, Q^{+}_{s\,lm}]U^{-1} = 0$$

SO $\hat{N}^{+}_{AB},\ Q^{+}_{lm},\ C^{+}_{lm}$ FORM A COMPLETE SET OF CANONICAL VARIABLES WITH CCR

FACTORIZATION OF IR DYNAMICS ON OPERATORS

USE THE HEISENBERG PICTURE: OPERATORS EVOLVE IN TIME, STATES DO NOT

$$O^+ = \Omega^{-1} O^- \Omega$$

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CCR: $\quad Q^\pm_{lm} = -i \dfrac{\partial}{\partial C^\pm_{lm}}$

CCR+MATCHING CONDITIONS:

$$[Q^\pm_{lm}, \Omega] = -i \frac{\partial \Omega}{\partial C^\pm_{lm}} = 0 \qquad [C^\pm_{lm}, \Omega] = 0 \to \Omega = \Omega(\hat{N})$$

HEISENBERG TIME EVOLUTION INDEPENDENT OF ALL IR DEGREES OF FREEDOM!

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FACTORIZATION OF HEISENBERG TIME EVOLUTION IMPLIES THAT IN A BASIS OF EIGENSTATES OF DRESSED VARIABLES, THE (SCHROEDINGER) TIME EVOLUTION IS

$$\Omega \sum_A C_A|A\rangle|C_{lm}\rangle = \sum_{AB} C_A \Omega^A_B |B\rangle|C_{lm}\rangle$$

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CAN WE CONSIDER THE BOUNDARY GRAVITON A LABEL OF A SUPERSELECTION SECTOR? NO BECAUSE BOOSTS AND ROTATIONS ACT AS CKVs ON THE CELESTIAL SPHERE, SO

$$R|C_{lm}\rangle \neq |C_{lm}\rangle$$

THE ORIGIN OF THIS PROBLEM IS SIMPLE: LORENTZ DOES NOT COMMUTE WITH SUPERTRANSLATIONS.

HENCE: ALL $|C_{lm}\rangle$ HAVE ZERO ENERGY, BUT THEY ARE NOT LORENTZ INVARIANT

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CAN WE DO BETTER? CAN WE DEFINE A LORENTZ THAT DOES NOT ACT ON THE SOFT VARIABLES AND STILL HAS THE CORRECT ACTION ON HARD VARIABLES?

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KEY IDEA OF arxiv:1808.02987 [hep-th]:
USE DRESSED VARIABLES.

THAT PAPER GAVE AN IMPLICIT CONSTRUCTION OF THE LORENTZ GENERATORS.
NOW WE CAN BE EXPLICIT.

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EXPLICIT FORM OF ROTATIONS

$$J(\Psi) = \frac{1}{8\pi G}\int_{I^+} du d^2\theta\sqrt{\gamma}\epsilon^{AL}\partial_L\Psi\left[\frac{1}{4}D^B D_B D^C \check{C}_{CA} - D^B D_A D^C \check{C}_{CB} + T_{uA}\right]$$

$$\check{C}_{AB} = \int_{-\infty}^{u} dv\hat{N}_{AB}(v) \equiv U\int_{-\infty}^{u} dv N_{AB}(v)U^{-1}$$

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COMMUTES WITH SOFT VARIABLES AND ACTS ON RADIATIVE VARIABLES AS

$$\{J(\Psi), \hat{N}_{AB}\} = \mathcal{L}_\Psi \hat{N}_{AB}$$

CONCLUSIONS

- A DUAL SUPERTRANSLATION CHARGE CAN BE DEFINED BY CHANGING THE REALITY CONDITION ON THE BOUNDARY GRAVITON IN ASYMPTOTICALLY FLAT SPACETIMES.
- IT SEEMS POSSIBLE TO INTERPRET THE SYMMETRY GENERATED BY DUAL SUPERTRANSLATION AS A GAUGE SYMMETRY
- THE GAUGE SYMMETRY CAN BE USE TO MAKE THE BOUNDARY GRAVITON VANISH LOCALLY ON THE CELESTIAL SPHERE
- THE BOUNDARY GRAVITON MAY NEVERTHELESS DEFINE A NONTRIVIAL BUNDLE ON THE CELESTIAL SPHERE. THIS INTERPRETATION MAKES THE TAUB-N.U.T. METRIC (ASYMPTOTICALLY) NONSINGULAR AND FREE OF CTC FOR A CERTAIN RANGE OF PARAMETERS

- PREVIOUS WORK HAS SHOWN THAT THERE EXISTS A CANONICAL TRANSFORMATION THAT MAKES RADIATIVE VARIABLES COMMUTE WITH BMS CHARGES AND BOUNDARY GRAVITONS

- USING THIS CANONICAL TRANSFORMATION WE MADE EXPLICIT —FOR THE ROTATION SUBGROUP OF LORENTZ— A PROPOSAL FOR A NEW DEFINITION OF LORENTZ CHARGES MADE RECENTLY BY JAVADINEZHAD KOL AND MYSELF

- THE NEW CHARGES COMMUTE WITH THE BOUNDARY GRAVITON AND THE BMS CHARGES BUT ACT IN THE USUAL WAY ON RADIATIVE VARIABLES.

- THE EXPLICIT CONSTRUCTION OF BOOSTS AND VERIFICATION OF CLOSURE OF THE LORENTZ ALGEBRA IS BEING WORKED OUT AT PRESENT (WITH JAVADINEZHAD AND KOL)