Quantum Gravity via Higher Spins and Three-dimensional Bosonization Duality

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Main Messages

- One of the main ideas behind HSGRA is to construct a toy model of Quantum Gravity. AdS/CFT, strings and SUGRA's indicate that one may need to embed the graviton into an infinite multiplet of fields with unbounded spin.
- Until recently there has not been a single example worked out in detail (action, quantization, ...)
- We construct an example of a complete toy-HSGRA, which we quantize and discuss how it complies with the no-go's, AdS/CFT duality
- In AdS this toy-HSGRA is related to physics via AdS/CFT and Chern-Simons Matter theories. It helps to prove the three-dimensional bosonization conjecture at the level of three-point functions...

No-go's

quantizing gravity via HSGRA = constructing classical HSGRA

Old and Flat:

global: (Coleman-Mandula, Weinberg) imply $S = 1$

local: (Bekaert, Boulanger, Leclercq; Tseytlin, Roiban; Ponomarev, E.S.; ...) imply that there is no sensible solution to the Noether procedure

New and AdS:

global: (Maldacena, Zhiboedov; Boulanger, Ponomarev, E.S., Taronna; Alba, Diab, Stanev): imply $S =$ Free CFT

local: (Maldacena, Simmons-Duffin, Zhiboedov; Erdmenger, Bekaert, Ponomarev, Sleight; Taronna, Sleight; Ponomarev) imply that there is no sensible solution to the Noether procedure. Quartic $\sim$ Exchange

No-go's

At present there are **only three well-defined** examples of Higher Spin Gravities that are **normal** field theories

- generalization of the $3d$ Chern-Simons formulation of gravity — replacing sl_2 with any $\mathfrak{g} > sl_2$ (Blencowe; Campoleoni, Fredenhagen, Pfenninger, Theisen; Henneaux, Rey; Gaberdiel, Gopakumar);
- Conformal Higher Spin Gravity — extension of the conformal gravity (Tseytlin, Segal; Bekaert, Joung, Mourad; Adamo, Tseytlin)
- Chiral Higher Spin Gravity (Metsaev; Ponomarev, E.S.; Ponomarev; E.S., Tran, Tsulaia; E.S.)

They are not plagued by the usual problems like non-locality

Formal HSGRA: Vasiliev; Bekaert, Grigoriev, E.S.; Grigoriev, E.S.; Sharapov, E.S.; FCS: Bonezzi, Boulanger, Sezgin, Sundell; Collective-Dipole: Jevicki et al

Chiral HSGRA in Minkowski

Self-dual Yang-Mills in Lorentzian signature is a useful analogy

- the theory is non-unitary due to the interactions ($A_\mu \to \Phi^{\pm}$)

$$\mathcal{L} = \Phi^{-}\Box\Phi^{+} + V^{++-} + V^{--+} + V^{++--}$$

- the tree-level amplitudes vanish, $A_{\text{tree}} = 0$
- the one-loop amplitudes do not vanish, are rational and coincide with $(++...+)$ of pure QCD
- speculations that a lot can be learned about QCD from SDYM ...

Chiral HSGRA in Minkowski

Likewise ... Chiral HSGRA is a HS theory $s = 0, 1, 2, 3, ...$

- the theory is non-unitary due to $\lambda_1 + \lambda_2 + \lambda_3 > 0$ in the vertex

$$\mathcal{L} = \sum_{\lambda} \Phi^{-\lambda} \Box \Phi^{+\lambda} + \sum_{\lambda_i} \frac{l_{\text{Pl}}^{\lambda_1+\lambda_2+\lambda_3-1}}{\Gamma(\lambda_1+\lambda_2+\lambda_3)} V^{\lambda_1,\lambda_2,\lambda_3}$$

  where (light-cone gauge is very close to the spinor-helicity language)

$$V^{\lambda_1,\lambda_2,\lambda_3} \sim [12]^{\lambda_1+\lambda_2-\lambda_3} [23]^{\lambda_2+\lambda_3-\lambda_1} [13]^{\lambda_1+\lambda_3-\lambda_2}$$

- the tree-level amplitudes vanish, $A_{\text{tree}} = 0$
- **no UV divergences!** One-loop amplitudes do not vanish, but are rational. All loops are proportional to the number of effective degrees of freedom, which vanishes in ζ-function regularization (Beccaria, Tseytlin), so loops can be made to vanish

Chiral HSGRA in Minkowski

some other properties:

- stringy 1: the spectrum contains $s = 0, (1), 2, (3), 4, ...$
- stringy 2: admit Chan-Paton factors, $U(N)$, $O(N)$ and $USp(N)$
- stringy 3: we have to deal with spin sums $\sum_s$ (worldsheet takes care of this in string theory) and ζ-function helps
- the action is nontrivial and contains parts of YM and Gravity
- consistent with Weinberg etc. $S = 1$ (in Minkowski)
- Chiral HSGRA is the only one in $4d$ Minkowski space. No-go for unitary theories (Ponomarev, E.S.), in addition to many other

and more ...

- this is the first (and the only) example of a HSGRA that was quantized
- toy model: we seem to have found a very complicated higher spin inspired way to get $S = 1$, but the graviton is there
- the Minkowski background is really unfortunate for HSGRA and, in fact, the most popular hypothetical HSGRA are AdS-HSGRA (holographic analog of $S = 1$ is $S =$ free CFT (Maldacena, Zhiboedov; Boulanger, Ponomarev, E.S., Taronna), but there are other options)

if we can jump to AdS then all drawbacks will turn into virtues. Thanks to AdS/CFT, there is a deep relation between HSGRA and many other models that describe physics

Chiral HSGRA in AdS

With the help of Metsaev, 2018 it is possible to uplift the chiral theory to AdS_4. Now it is less trivial

- we still have cubic action of the form

$$\mathcal{L} = \sum_{\lambda} \Phi^{-\lambda} \Box \Phi^{+\lambda} + \sum_{\lambda_i} \frac{g}{\Gamma(\lambda_1 + \lambda_2 + \lambda_3)} V^{\lambda_1, \lambda_2, \lambda_3}$$

- it is not obstructed by nonlocalities
- **the flat space story guarantees the absence of UV-divergences in AdS. Therefore, the chiral HSGRA should be a consistent quantum gravity toy-model**
- **three-point function are known and are not trivial (do not belong to any free CFT), $S = 1$ triviality is not there anymore**

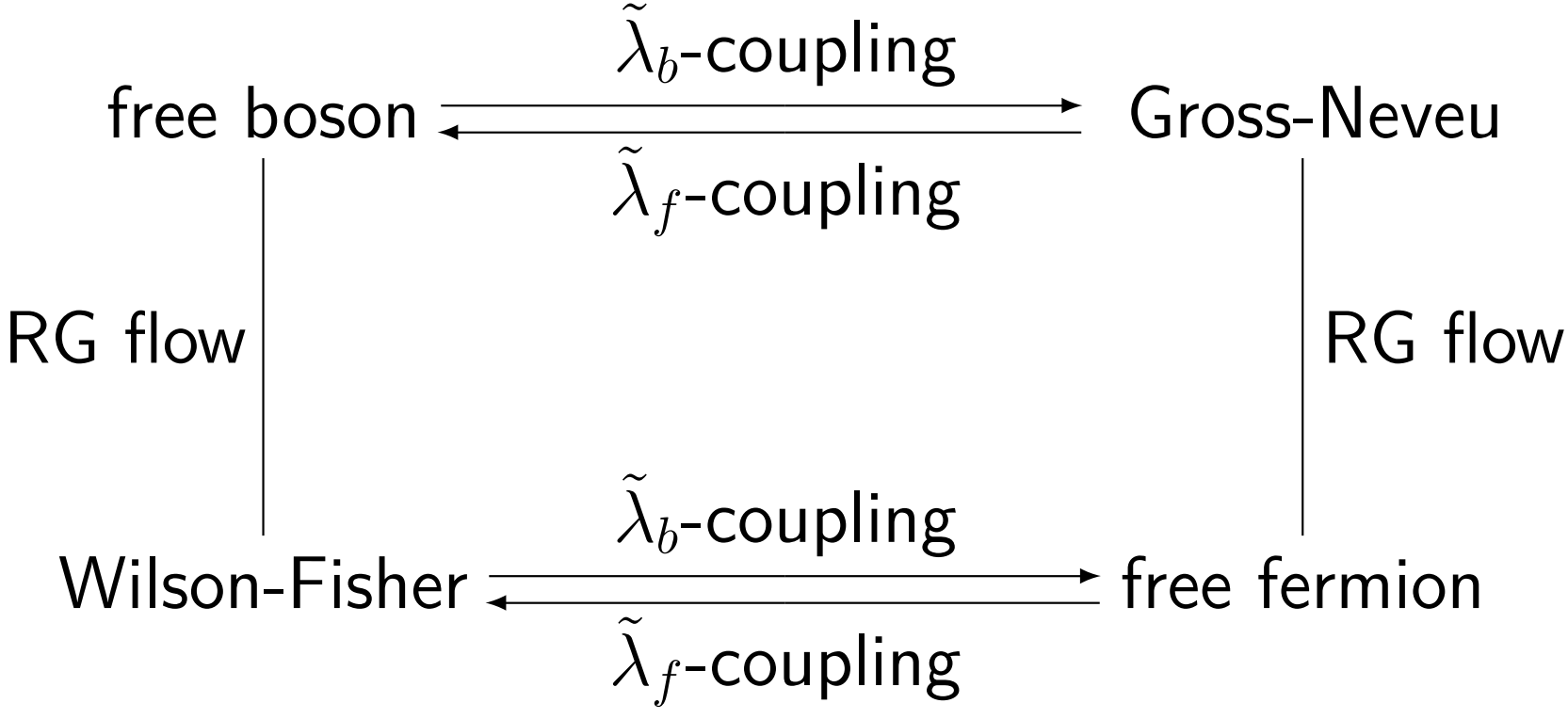
Higher Spin AdS/CFT

In AdS_4/CFT_3 one can do much better (interesting) — there exists a large class of models, Chern-Simons Matter theories (extends to ABJ(M))

$$\frac{k}{4\pi}S_{CS}(A) + \text{Matter} \begin{cases} \int (D\phi)^2 \\ \int (D\phi)^2 + \phi^2\sigma \\ \int \bar{\psi} \not{D} \psi \\ \int \bar{\psi} \not{D} \psi + (\bar{\psi}\psi)\sigma \end{cases}$$

- describe physics (Ising, ...)
- break parity in general (Chern-Simons)
- two generic parameters $\lambda = N/k$, $1/N$ (λ continuous for N large)
- exhibit a number of remarkable dualities, e.g. $3d$ bosonization duality (Aharony, Alday, Bissi, Giombi, Karch, Maldacena, Minwalla, Prakash, Seiberg, Tong, Witten, Yacobi, Yin, Zhiboedov, ...)

Higher Spin AdS/CFT



$\gamma(J_s)$ at order $1/N$ (Giombi, Gurucharan, Kirillin, Prakash, E.S.) confirm the duality. 4, 5-loop $1/N^2$ results in Gross-Neveu and Wilson-Fisher (Manashov, E.S., Strohmaier) seem hard to extend in λ

Light-Front Bootstrap

(anti)-Chiral theories are building blocks of the unitary HSGRA. At the cubic level the HSGRA dual of Chern-Simons Matter theories result from the 'direct' sum of the chiral and anti-chiral theories:

$$\boldsymbol{V_3 = V_{chiral} \oplus \bar{V}_{chiral} \quad \leftrightarrow \quad \langle JJJ \rangle}$$

The chiral theories are built by directly constructing the generators of the conformal algebra $so(3,2)$ (like in the old days of string theory)

$$P^a\,, K^a\,, D\,, L^{ab} \qquad\qquad P^- = \int \Phi_p^{\lambda\dagger} ... \Phi_p^{\lambda} + \mathcal{O}(\Phi^3)$$

We can ignore the AdS-part, **with chiral HSGRA we are just constructing a nonlinear realization of the conformal algebra — Light-front bootstrap**

Light-Front Bootstrap

Maldacena, Zhiboedov found out/conjectured the three-point functions in CS-Matter theories to be (θ is related to N, k in a complicated way):

$$\langle JJJ\rangle \sim \cos^2\theta\langle JJJ\rangle_b + \sin^2\theta\langle JJJ\rangle_f + \cos\theta\sin\theta\langle JJJ\rangle_o$$

Slightly-broken higher spin symmetry should guarantee that

Gluing of the chiral and anti-chiral theories gives just that

We get all the (missing) three-point functions, which is the first prediction of HSGRA that is ahead of the CFT side

The θ turns out to have something to do with $U(1)$ EM duality rotations

This can prove the $3d$ bosonization duality provided shown to be true for higher point functions since the correlation functions are fixed irrespective of what the constituents are (bosons or fermions)!

Light-Front Bootstrap

Some other results

- there is one-to-one between spinor-helicity three-point amplitudes, vertices in AdS_4 and CFT_3 three-point functions

  $$[12]^{\lambda_1+\lambda_2-\lambda_3}[23]^{\lambda_2+\lambda_3-\lambda_1}[13]^{\lambda_1+\lambda_3-\lambda_2} \sim V^{\lambda_1,\lambda_2,\lambda_3} \sim \langle J_{\lambda_1} J_{\lambda_2} J_{\lambda_3} \rangle$$

  see also (Farrow, Lipstein, McFadden)

- we see slightly more CFT_3-structures that was previously found

- **(anti)-chiral theories give two non-unitary solutions for three-point functions. What is CFT dual? (looks similar to the Fishnet)**

Concluding Remarks

- At least some of HSGRA seem to exist: chiral (also conformal). It reveals trivial S-matrix in flat space, but not in AdS
- Chiral HSGRA is a complete toy model with some stringy features and shows how gravity can be quantized thanks to higher spin fields: supersymmetry vs. higher spin symmetry
- It allows one to compute all three-point functions in Chern-Simons Matter theories, making new verifiable predictions, and prove the bosonization duality to this order. Nonlinear realization of the conformal algebra - Light-Front Bootstrap
- Chiral HSGRA's gives two more solutions for $\langle JJJ \rangle$ and it would be interesting to identify these (fishnet-like) CFT's

Thank you for your attention!