Quantum Gravity via Higher Spins and Three-dimensional Bosonization Duality

Quantum Field Theory meets Gravity

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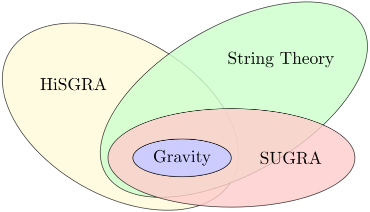
Main Messages

- One of the main ideas behind Higher Spin Gravity (HSGRA) is to construct a toy model of Quantum Gravity
- Until recently there has not been a single example worked out in detail (action, quantization, ...)
- We construct the first complete HSGRA — chiral HSGRA, which we quantize and it turns out to be UV finite
- Thanks to AdS/CFT in AdS this HSGRA is related to physics via Chern-Simons Matter theories. It helps to prove the three-dimensional bosonization conjecture at the level of three-point functions. It also leads to the first prediction of HSGRA for physics

Why higher spin fields are needed?



Various examples (not all)

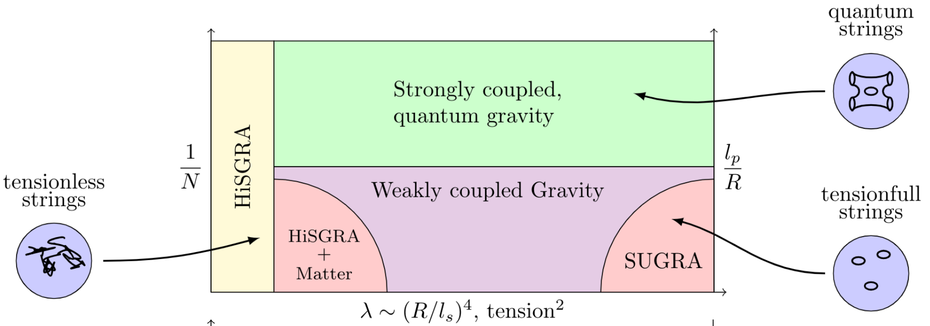
- string theory
- divergences in (SU)GRA's
- CFT's always have infinitely many operators and spin is unbounded

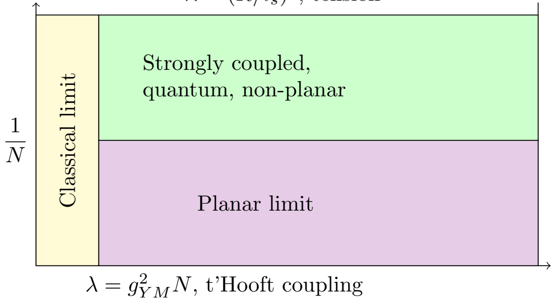
seem to indicate that quantization of gravity requires

- infinitely many fields
- for any $s > 0$ a spin-s field must be part of the spectrum

HSGRA is about finding the most minimalistic extension of gravity by massless, i.e. gauge, higher spin fields. Vast gauge symmetry should render it finite ...

HSGRA from Tensionless Strings, duals of weakly coupled CFT's





Sundborg;
Klebanov, Polyakov;
Sezgin, Sundell;
Beisert, Bianchi, Morales, Samtleben;
Leigh, Petkou

Quantizing Gravity via HSGRA = Constructing Classical HSGRA

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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

Three HSGRA in 2019

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

- generalization of the $3d$ Chern-Simons formulation of gravity — replacing sl_2 with any $\mathfrak{g} > sl_2$ (Blencowe; Bergshoeff et al; 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 Plan

Chiral HSGRA

Minkowski

trees, loops, UV finiteness

anti-de Sitter

new CFT's, $3d$ bosonization, bootstrap, complete AdS/CFT

de Sitter

$R + R^3$ corrections
Inflation

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

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

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

- the tree-level amplitudes vanish, $A_{\text{tree}} = 0$
- the one-loop amplitudes do not vanish, are rational and coincide with $(+ + ...+)$ of pure QCD

Likewise, Chiral HSGRA (Ponomarev, E.S.) 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, $A_{\text{tree}} = 0$, just like in SDYM (E.S., Tsulaia, Tung)

No UV Divergences!

The interactions are naively non-renormalizable, the higher the spin the more derivatives:

$$\boldsymbol{V^{\lambda_1,\lambda_2,\lambda_3} \sim \partial^{\lambda_1+\lambda_2+\lambda_3}\Phi^3}$$

but there are **no UV divergences!** Some loop momenta eventually factor out, just as in $\mathcal{N}=4$ SYM, but ∞ many more times. One-loop amplitudes do not vanish, but are rational, like in SDYM

All loops are proportional to the number of effective degrees of freedom, which vanishes in ζ-function regularization (Klebanov, Giombi, Safdi; ...; Beccaria, Tseytlin), so loops can be made to vanish. To be expected from the Weinberg theorem etc.

$$1+2\sum_{s>0}1=0 \qquad\qquad \frac{1}{360}+\sum_s\left(\frac{1}{180}-\frac{s^2}{24}+\frac{5s^4}{24}\right)=0$$

Chiral HSGRA in Minkowski

- **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)

The Minkowski background is really unfortunate for HSGRA. If we can jump to AdS then all drawbacks will turn into virtues. There is a relation between HSGRA and physics via AdS_4/CFT_3 (Klebanov, Polyakov, Sezgin, Sundell, Giombi, Yin, ...)

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**

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, quantum Hall, ...)**
- 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, ...)

Chern-Simons Matter theories and dualities

$$\begin{tikzcd}
\text{free boson} \arrow[r, shift left, "\tilde{\lambda}_b\text{-coupling}"] \arrow[d, dash, "\text{RG flow}"'] & \text{Gross-Neveu} \arrow[l, shift left, "\tilde{\lambda}_f\text{-coupling}"] \arrow[d, dash, "\text{RG flow}"] \\
\text{Wilson-Fisher} \arrow[r, shift left, "\tilde{\lambda}_b\text{-coupling}"] & \text{free fermion} \arrow[l, shift left, "\tilde{\lambda}_f\text{-coupling}"]
\end{tikzcd}$$

$\gamma(J_s)$ at order $1/N$ (Giombi, Gurucharan, Kirillin, Prakash, E.S.) confirm the duality. The simplest operators are $J_s = \phi D...D\phi$ or $J_s = \bar{\psi}\gamma D...D\psi$. 4, 5-loop $1/N^2$ results in Gross-Neveu and Wilson-Fisher (Manashov, E.S., Strohmaier) seem hard to extend in λ

(anti)-Chiral theories are building blocks of other HSGRA's. 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)

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

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

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):

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

Follow from slightly-broken higher spin symmetry: $\partial\cdot J = \frac{1}{N}[JJ]$

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 — the correlators of J's get fixed irrespective of what the constituents are (bosons or fermions)!

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 HSGRA. It reveals trivial S-matrix in flat space, but not in AdS. It exists in dS as well: prediction for R vs. R^3 corrections in cosmology
- Chiral HSGRA is a complete toy model with some stringy features and shows how gravity can be quantized thanks to higher spin fields: **no UV divergences, 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!