

# **(Quantum) Higher Spin Gravity and some applications to Physics**

**OIST — Online Seminar**

Evgeny Skvortsov, Albert Einstein Institute

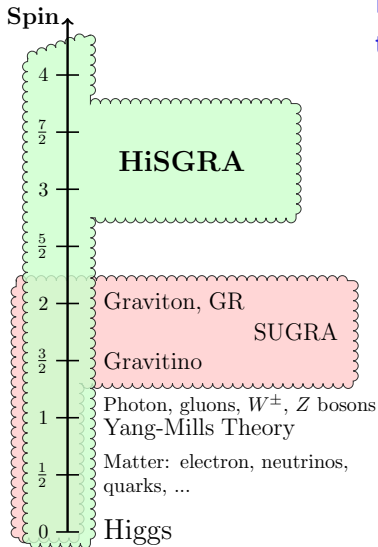
with N. Boulanger, S. Giombi, M. Gunaydin, Gurucharan, V. Kirilin, A.  
Manashov, D. Ponomarev, S. Prakash, E. Sezgin, M. Tsulaia, M. Taronna,  
T. Tran

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- Higher Spin Gravities (HiSGRA) — the most minimal extensions of gravity with massless higher spin fields — toy models of Quantum Gravity. The idea is that massless fields  $\rightarrow$  gauge fields; more gauge symmetries  $\rightarrow$  less counterterms  $\rightarrow$  Quantum Gravity. No free lunch: HiSGRA are hard to construct and there are very few (no-go's)
- We constructed the first complete HiSGRA — Chiral HiSGRA, which we quantized and it turns out to be UV-finite
- In AdS Chiral HiSGRA is related to physics via AdS/CFT and Chern-Simons Matter theories (Ising, etc.). It helps to prove the three-dimensional bosonization conjecture at the level of three-point functions. It also leads to the first prediction of HiSGRA for physics
- In Flat space Chiral HiSGRA is related to SDYM and QCD (reproduces all-plus helicity amplitudes up to some HS dressing)

- Overview of HiSGRA's: AdS/CFT, no-go's, ...
- HiSGRA as models of Quantum Gravity
- Chiral HiSGRA in flat: UV-finiteness and SDYM/QCD
- Chiral HiSGRA in AdS:  $3d$  bosonization duality

## Why higher spins?



## Different spins lead to very different types of theories/physics:

- $s = 0$ : Higgs
- $s = 1/2$ : Matter

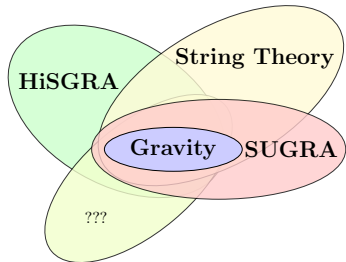
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- $s = 1$ : Yang-Mills, Lie algebras
- $s = 3/2$ : SUGRA and supergeometry, need graviton and ...
- $s = 2$  (graviton): GR and Riemann Geometry, no color (Boulanger et al)
- $s > 2$ : HiSGRA and String theory, but the graviton is there too!

## Why higher spins?

Various examples (not all)

- string theory
- divergences in (SU)GRA's
- Quantum Gravity via AdS/CFT



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

HiSGRA is to find the most minimalistic extension of gravity by massless, i.e. gauge, higher spin fields. Vast gauge symmetry should render it finite.

**Quantizing Gravity via HiSGRA = Constructing Classical HiSGRA**

## What Higher Spin Problem is

A massless spin- $s$  particle can be described by a rank- $s$  tensor

$$\delta\Phi_{\mu_1\dots\mu_s} = \nabla_{\mu_1}\xi_{\mu_2\dots\mu_s} + \text{permutations}$$

which generalizes  $\delta A_\mu = \partial_\mu\xi$ ,  $\delta g_{\mu\nu} = \nabla_\mu\xi_\nu + \nabla_\nu\xi_\mu$

**Problem:** find a nonlinear completion (action, gauge symmetries)

$$S = \int (\nabla\Phi)^2 + \mathcal{O}(\Phi^3) + \dots \quad \delta\Phi_{\dots} = \nabla.\xi_{\dots} + \dots$$

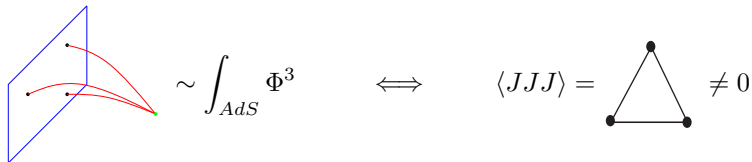
and prove that it is UV-finite, hence a Quantum Gravity model

## What Higher Spin Problem is: AdS/CFT

In the context of AdS/CFT: gauge fields are dual to conserved currents

$$\partial^m J_{ma_2\dots a_s} = 0 \quad \iff \quad \delta\Phi_{\mu_1\dots\mu_s} = \nabla_{\mu_1}\xi_{\mu_2\dots\mu_s}$$

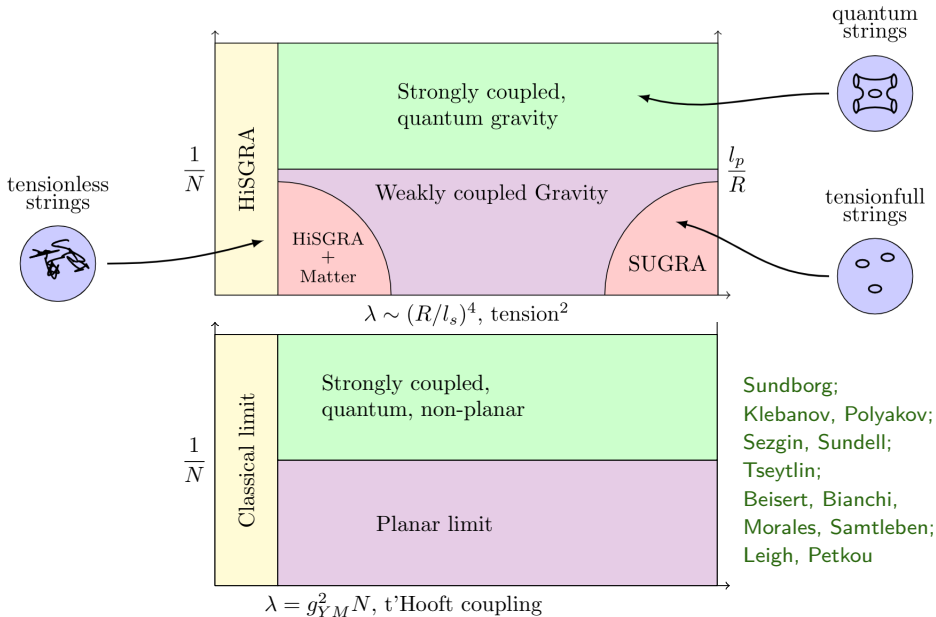
Free CFTs, e.g. free SYM or free scalar/fermion CFT, have  $\infty$ -many HS currents  $\mathbf{J}_s = \text{Tr}[\phi \partial\dots\partial \phi]$ , hence, the dual theory has to be a HiSGRA (Sundborg; Klebanov, Polyakov; Sezgin, Sundell; Leigh, Petkou; Jevicki et al; ...):


$$\sim \int_{AdS} \Phi^3 \quad \iff \quad \langle JJJ \rangle = \triangle \neq 0$$

and **Gravity duals of even free CFT's are interacting theories**

**Weakly coupled CFT's do not have a large gap! Therefore, there is no well-defined semi-classical local gravitational dual by default**

# HiSGRA from Tensionless Strings, duals of weakly coupled CFT's





## Some 'tensionless pairs' /duals of weakly-coupled CFT's

- free SYM vs. ??HiSGRA+Matter (Sundborg; Sezgin, Sundell; Beisert, Bianchi, Morales, Samtleben);
- Fishnet vs. ?? strings (Caetano, Kazakov; Gromov, Sever)
- $\text{Sym}^N(\mathbb{T}^4)$  vs. strings on  $AdS_3 \times S^3 \times \mathbb{T}^4$  (Gaberdiel, Gopakumar; Eberhardt, Gaberdiel);
- free scalar/fermion CFT's, Wilson-Fisher/Gross-Neveu, Chern-Simons Matter theories up to ABJ vs. strings and ??HiSGRA (Klebanov, Polyakov, Sezgin, Sundell, Petkou, Leigh, Chang, Minwalla, Sharma, Yin, Giombi, Prakash, Trivedi, Wadia);
- ?? CS-Matter-like vs. Chiral HiSGRA (Metsaev; Ponomarev, E.S.; Tung, Tsulaia, E.S.)

# Power of higher spin symmetry

## know your friend/enemy

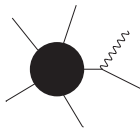
- too small symmetry: nothing can be computed even with a theory
- too big symmetry: everything can be computed even without a theory
- higher spin symmetry: **almost** everything can be computed and there is **no** theory

## Higher spin symmetry constraints on S-matrix

Let's study asymptotic higher spin symmetry (HSS) in Minkowski

$$\delta\Phi_{\mu_1\dots\mu_s}(x) = \partial_{\mu_1}\xi_{\mu_2\dots\mu_s}$$

Weinberg low energy theorem, also Coleman-Mandula theorem:



$$\sum_i g_i p_{\mu_1}^i \dots p_{\mu_{s-1}}^i = 0$$

- $s = 1$ , charge conservation  $\sum g_i = 0$
- $s = 2$ , equivalence principle  $\sum g_i p_{\mu}^i = 0 \rightarrow g_i = g$
- $s > 2$ , too many conservation laws and  $S = 1$

May be massless higher spin fields confine? or do not exist?

## Local vs. Global tension

**Global picture:** The  $S$ -matrix has to be trivial,  $S = 1$ , whenever there is at least one massless higher spin  $s > 2$  particle

**Local picture:** The same time, for every triplet of helicities,  $\lambda_{1,2,3}$  there is a nontrivial cubic vertex/amplitude (Brink, Bengtsson<sup>2</sup>, Linden; ...)

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

**Puzzle:** Why do we have cubic amplitudes for all possible helicities, but do not seem to have theories that apply those?

**Possible resolutions:** (1) that's life and there may not exist any HiSGRA; (2) **there are some (very few!) HiSGRA's, but the interactions are fine-tuned to give  $S = 1$  in Minkowski. There are other backgrounds, for example AdS, where  $S \neq 1$**

## Higher spin symmetry constraints on holographic S-matrix

Let's study asymptotic higher spin symmetry (HSS) in anti-de Sitter

$$\delta\Phi_{\mu_1\dots\mu_s}(x) = \nabla_{\mu_1}\xi_{\mu_2\dots\mu_s} \quad \iff \quad \partial^m J_{ma_2\dots a_s} = 0$$

$\Downarrow$   
**free CFT**

Given a CFT in  $d \geq 3$  with stress-tensor  $J_2$  and at least one higher-spin current  $J_s$ , one can prove that it is a free CFT in disguise [Maldacena, Zhiboedov](#); [Boulanger, Ponomarev, E.S., Taronna; Alba, Diab, Stanev](#)

**This essentially proves the duality no matter how the bulk theory is realized. It may not even exist!**

This is a generalization of the Weinberg and Coleman-Mandula theorems to AdS/CFT: higher spin symmetry implies

**holographic  $S = \text{free CFT}$**

## Higher spin symmetry constraints on holographic S-matrix

Let's study asymptotic higher spin symmetry (HSS) in anti-de Sitter

$$\delta\Phi_{\mu_1\dots\mu_s}(x) = \nabla_{\mu_1}\xi_{\mu_2\dots\mu_s} \iff \partial^m J_{ma_2\dots a_s} \neq 0$$

Large- $N$  critical vector model (Wilson-Fisher)

$$S = \int d^3x \left( (\partial\phi^i)^2 + \frac{\lambda}{4!} (\phi^i\phi^i)^2 \right)$$

should be dual to the same theory for  $\Delta = 2$  boundary conditions on  $\Phi(x)$  (Klebanov, Polyakov). **This duality is kinematically related to the first one** (Hartman, Rastelli; Giombi, Yin; Bekaert, Joung, Mourad).

**holographic  $S =$  Large- $N$  Ising**

This can be extended to Chern-Simons Matter theories, (Chang, Minwalla, Sharma, Yin, Giombi, Prakash, Trivedi, Wadia; Aharony; Maldacena, Zhiboedov, ...)

# Where Field theory cries...

Ingenious: invert AdS/CFT and reconstruct the dual theory from free CFT  
 (Bekaert, Erdmenger, Ponomarev, Sleight; Taronna, Sleight)

$$\# \text{ (circle with 3 wavy lines)} = \# \text{ (triangle)} \quad \text{Costa et al}$$

$$\text{(circle with 4 wavy lines)} + \text{(circle with 2 wavy lines)} + t, u = \text{(square)} = \langle JJJJ \rangle$$

But there is a big 'but' lurking around the corner:

$$\text{(circle with 2 wavy lines)} + t, u = 2 \langle JJJJ \rangle \quad \text{(circle with 4 wavy lines)} = -\langle JJJJ \rangle \sim \Phi^2 \frac{1}{\square + \Lambda} \Phi^2$$

**Quartic vertex  $\sim$  exchange. Field theory does not like that!**

## S-matrix summary

We see that asymptotic higher spin symmetries (HSS)

$$\delta\Phi_{\mu_1\dots\mu_s}(x) = \nabla_{\mu_1}\xi_{\mu_2\dots\mu_s}$$

seem to completely fix (holographic)  $S$ -matrix to be

$$S_{\text{HiSGRA}} = \begin{cases} 1^{***}, & \text{flat space (**super-soft vs. Veneziano**)} \\ \text{free CFT,} & \text{asymptotic AdS, unbroken HSS} \\ \text{Chern-Simons Matter,} & \text{asymptotic AdS}_4, \text{ slightly-broken HSS} \end{cases}$$

**Trivial/known  $S$ -matrix can still be helpful for QG toy-models**

**The most interesting applications are for  $AdS_4/CFT^3$  and three-dimensional dualities (power of HSS is underexplored)**

Both Minkowski and AdS cases reveal certain non-localities to be tamed. HSS mixes  $\infty$  spins and derivatives, invalidating the local QFT approach



# List of HiSGRA that survived

**Quantizing Gravity via HiSGRA = Constructing Classical HiSGRA**

Therefore, HiSGRA can be good probes of the Quantum Gravity Problem

## Four classes of HiSGRA in 2020

**3d massless and partially-massless** (Blencowe; Bergshoeff et al; Campoleoni, Fredenhagen, Pfenninger, Theisen; Henneaux, Rey; Gaberdiel, Gopakumar; Grigoriev, Mkrtychyan, E.S.),  $S = S_{CS}$  for a HS extension of  $sl_2 \oplus sl_2$

$$S = \int \omega d\omega + \frac{2}{3}\omega^3$$

**3d conformal** (Pope, Townsend; Fradkin, Linetsky; Grigoriev, Lovrekovic, E.S.),  $S = S_{CS}$  for higher spin extension of  $so(3,2)$

**4d conformal** (Tseytlin, Segal; Bekaert, Joung, Mourad; Adamo, Tseytlin), HS extension of Weyl gravity

$$S = \int \sqrt{g} W^2 + \dots$$

**4d massless chiral** (Metsaev; Ponomarev, E.S.; Ponomarev; E.S., Tran, Tsulaia; E.S.). **This talk!**

**The theories avoid all the no-go theorems. Surprisingly, all of them have simple actions and are clearly well-defined**

## Other proposals

- **Reconstruction:** invert AdS/CFT
  - Brute force (Bekaert, Erdmenger, Ponomarev, Sleight; Taronna, Sleight)
  - Collective Dipole (Jevicki, Mello Koch et al)
  - Holographic RG (Leigh et al, Polchinski et al)
- **Formal HiSGRA:** constructing  $L_\infty$ -extension of HS algebras, i.e. a certain odd  $Q$ ,  $QQ = 0$ , and write AKSZ sigma model

$$dW = Q(W)$$

(Vasiliev; E.S., Sharapov, Bekaert, Grigoriev, E.S.; Grigoriev, E.S.; E.S., Sharapov, Tran; Bonezzi, Boulanger, Sezgin, Sundell; Neiman)

- **IKKT matrix model for fuzzy  $H_4$**  (Steinacker; Sperling, Steinacker)

Certain things do work, but the general rules are yet to be understood, e.g. non-locality, relation to field theory, quantization, ...

# Higher Spin Gravity as Quantum Gravity?

## Quantum Effects in Holographic HiSGRA

Given that Chiral HiSGRA is the only one with action and propagating fields, people have to be very creative to say anything about quantum corrections:

- AdS/CFT-inspired: use one-loop determinants to probe the spectrum on various backgrounds;
- AdS/CFT-inspired: use AdS unitarity cuts as to reduce calculation of loops to manipulation with CFT data;
- explicit computations in Chiral HiSGRA

Warming up: HiSGRA can look like topological theories. Indeed, suppose we are in Minkowski space

$$S = \sum_s \int \Phi_{a_1 \dots a_s} \square \Phi^{a_1 \dots a_s} \quad \Phi_{a_1 \dots a_s} = \partial_{a_1} \xi_{a_2 \dots a_s}$$

The one-loop partition function is

$$Z^2 = \frac{1}{\det_{s=0} \square \det_{s=1} \square \det_{s=2} \square \dots} = \frac{1}{(\det_{s=0} \square)^{\nu_{eff}}}$$

Beccaria, Tseytlin suggested to cancel (de)numerators, so that

$$\nu_{eff} = 1 + \sum_{s>0} 2 = 1 + 2\zeta(0) = 1 - 1 = 0$$

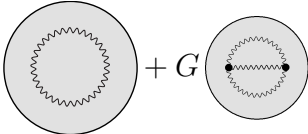
In AdS a naive cancellation is impossible

$$S = \sum_s \int \Phi_s K_s \Phi_s, \quad K_s = -\nabla^2 + M_s^2, \quad \delta\Phi_{a_1 \dots a_s} = \nabla_{a_1} \xi_{a_2 \dots a_s}$$

The one-loop partition function is

$$e^{-2F_{AdS}} = Z^2 = \frac{1}{\det K_0 \det K_1 \det K_2 \dots} \det \tilde{K}_0 \det \tilde{K}_1 \dots = ?$$

We also have predictions from AdS/CFT:  $Z_{CFT} = Z_{AdS}$

$$F_{AdS} = \frac{1}{G} S_{cl}[AdS] + \text{[Diagram 1]} + G \text{[Diagram 2]} + \dots$$


The leading piece is the classical action and is not available, but let's look at the subleading term — **one-loop determinants**

In AdS a naive cancellation is not possible

$$S = \sum_s \int \Phi_s K_s \Phi_s, \quad K_s = -\nabla^2 + M_s^2, \quad \delta\Phi_{a_1 \dots a_s} = \nabla_{a_1} \xi_{a_2 \dots a_s}$$

The one-loop partition function is

$$e^{-2F_{AdS}} = Z^2 = \frac{1}{\det K_0 \det K_1 \det K_2 \dots} \frac{\det \tilde{K}_0 \det \tilde{K}_1 \dots}{\det K_0 \det K_1 \det K_2 \dots} = ?$$

We also have predictions from AdS/CFT:  $Z_{CFT} = Z_{AdS}$

$$F_{AdS} = \frac{1}{G} F_{AdS}^0 + \mathbf{F}_{AdS}^1 + \mathcal{O}(G)$$

$$F_{CFT} = N \mathbf{F}_{CFT}^0 + F_{CFT}^1 + \mathcal{O}\left(\frac{1}{N}\right)$$

For example, the free scalar in 3d gives  $\mathbf{F}_\phi^3 = \frac{1}{16} (2 \log 2 - \frac{3\zeta(3)}{\pi^2})$



It seems that we should be proving  $0 = 0$ , but this is not the case!

- Different backgrounds: Euclidian, global, thermal  $AdS_{d+1}$  spaces etc. allow us to get an access to  $a$ ,  $c$  anomaly coefficients, Casimir energy, sphere free energy
- Different spectrum of fields, e.g. all spins or even only vs.  $U(N)$  or  $O(N)$  CFT duals
- There can be various log-divergences that should either agree or cancel

$$F_{AdS,s} = -\zeta_s(0) \log \Lambda l - \frac{1}{2} \zeta'_s(0)$$

$\zeta$ 's for various fields were found by **Camporesi**, **Higuchi**, but we need to **sum over infinitely many fields, let's try zeta-function!**

An interesting pattern observed for a number of low dimensions  $d$ :  
(Giombi, Klebanov, Safdi, Tseytlin, Beccaria, ...)

- all integer spins:  $F_{AdS}^1 = 0$ , ok we have  $0 = 0$ ;
- for even spins:  $F_{AdS}^1 = F_{CFT}^0$ , so the duality can work if  $G^{-1} = N - 1$  and we have

$$F_{AdS} = (N - 1)F_{CFT}^0 + F_{CFT}^0 + \mathcal{O}(G)$$
$$F_{CFT} = (N - 1 + 1)F_{CFT}^0$$

Similar shifts of  $G$  are in Chern-Simons dual to topological strings  
(Sinha, Vafa) and for the usual SYM vs. IIB on  $AdS_5 \times S^5$  duality;

**It is hard to 'fake'**  $F_\phi^3 = \frac{1}{16}(2 \log 2 - \frac{3\zeta(3)}{\pi^2})$  **and similar numbers**

There is a general analytical proof of the conjecture (E.S, Tung) and its extension to non-integer dimension (Klebanov, Polyakov),  $AdS_{4.99}/CFT^{3.99}$

In particular, in  $AdS_4/CFT^3$  for Wilson-Fisher

$$\delta\tilde{F} = -\frac{\zeta(3)}{8\pi^2}$$

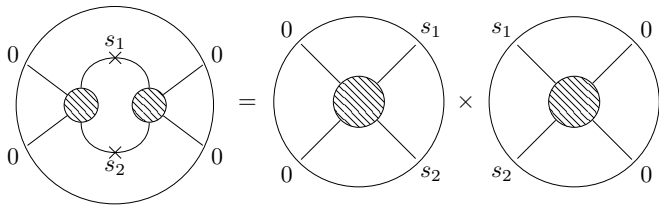
In particular, around  $AdS_{4.99}/CFT^{3.99}$  for Wilson-Fisher

$$\delta\tilde{F} = -\frac{\pi}{567}\epsilon^3 - \frac{13\pi}{6912}\epsilon^4 + \dots$$

**The  $\epsilon$ -expansion of free energy of the Wilson-Fisher CFT is reproduced as one-loop effect in Higher Spin Gravity**

## Unitarity cuts in AdS/CFT (non-invasive techniques)

One-loop four-point can be reconstructed (Ponomarev, Sezgin, E.S.)



from its double-cut following Fitzpatrick, Kaplan.

- the double-cut turns out to be higher spin invariant
- agreement with  $G^{-1} \sim N$  or  $G^{-1} \sim N \pm 1$

Chiral HiSGRA for  
Quantum Gravity and  
*3d* dualities

Unless we want/can bootstrap the  $S$ -matrix directly, we may resort to local field theory methods: we can take the physical d.o.f. and attempt to construct  $P_\mu$ ,  $L_{\mu\nu}$  directly

### Gauge symmetry is just a redundancy

It is convenient to do so in the light-cone gauge that eliminates all unphysical d.o.f., e.g.  $SU(N)$  YM is the theory of  $(N^2 - 1)$   $\Phi_{\pm 1}$  scalars and gravity is a theory of two scalars  $\Phi_{\pm 2}$

$$[J^{a-}, J^{b-}] = 0 \qquad [J^{a-}, P^-] = 0$$

Many important results have been first obtained in the LC gauge: quantization of strings, finiteness of  $\mathcal{N} = 4$  SYM

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

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

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

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

Chiral HiSGRA (Mesaev; Ponomarev, E.S.) has all  $s = 0, 1, 2, 3, \dots$

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

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

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

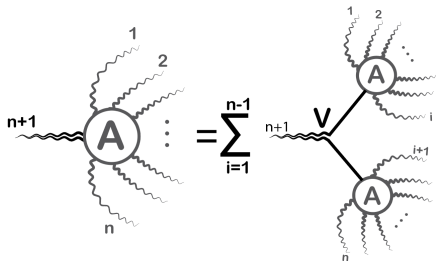
$$V^{\lambda_1, \lambda_2, \lambda_3} \sim [12]^{\lambda_1 + \lambda_2 - \lambda_3} [23]^{\lambda_2 + \lambda_3 - \lambda_1} [13]^{\lambda_1 + \lambda_3 - \lambda_2}$$

The relation to SDYM is deeper than it seems (Ponomarev), also similar to self-dual Gravity (Siegel; Krasnov)

**This is a unique solution once at least one higher spin field is in the game. Graviton and scalar are parts of one multiplet**



- the tree-level amplitudes vanish,  $A_{\text{tree}} = 0$ , just like in SDYM (E.S., Tsulaia, Tung)



which gives

$$A_n \sim \frac{1}{\Gamma(\Lambda_n - (n - 3)) \prod_{i=1}^n \beta_i^{\lambda_i - 1}} \frac{\alpha_n^{\Lambda_n - (n-2)} \beta_2 \dots \beta_{n-2} \mathbf{p}_n^2}{\beta_n \mathbb{P}_{12} \dots \mathbb{P}_{n-2, n-1}}$$

## No UV Divergences! One-loop finiteness

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

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

but there are **no UV divergences!** (E.S., Tsulaia, Tung) Some loop momenta eventually factor out, just as in  $\mathcal{N} = 4$  SYM, but  $\infty$  many more times. One-loop amplitudes do not vanish, but are rational

At one loop we find three factors: (1) SDYM or all-plus 1-loop QCD; (2) higher spin dressing to account for  $\lambda_i$ ; (3) total number of d.o.f.:

$$A_{\text{Chiral}}^{1\text{-loop}} = A_{\text{QCD}, 1\text{-loop}}^{++\dots+} \times D_{\lambda_1, \dots, \lambda_n}^{\text{HSG}} \times \sum_{\lambda} 1$$

- **stringy 1**: the spectrum is infinite  $s = 0, (1), 2, (3), 4, \dots$
- **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  $\zeta$ -function helps
- **stringy 4**: the action contains parts of YM and Gravity
- **stringy 5**: higher spin fields soften amplitudes
- consistent with Weinberg etc.  $S = 1^{***}$  (in Minkowski)
- gives all-plus QCD or SDYM amplitudes from a gravity

The Minkowski background is not the only one for HiSGRA. If we can jump to AdS then all drawbacks will turn into virtues.

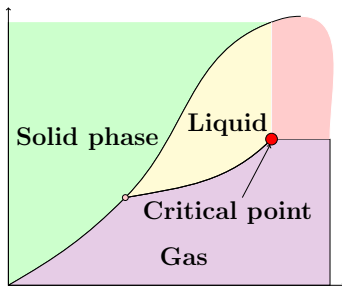
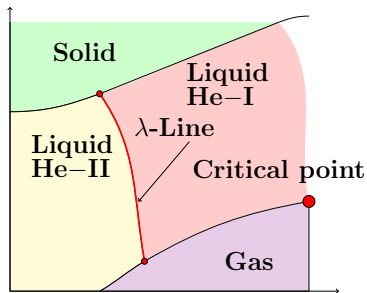
With the help of [Metsaev, 2018](#) it is possible to uplift Chiral Theory to  $AdS_4$ . Now it is less trivial

- we still have cubic action of the form

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

- it is not obstructed by nonlocalities
- **flat space story should guarantee the absence of UV-divergences in AdS. Therefore, the chiral HSGRA should be a consistent quantum gravity toy-model**
- **holographic three-point function are known and are not trivial: do not belong to any free CFT**

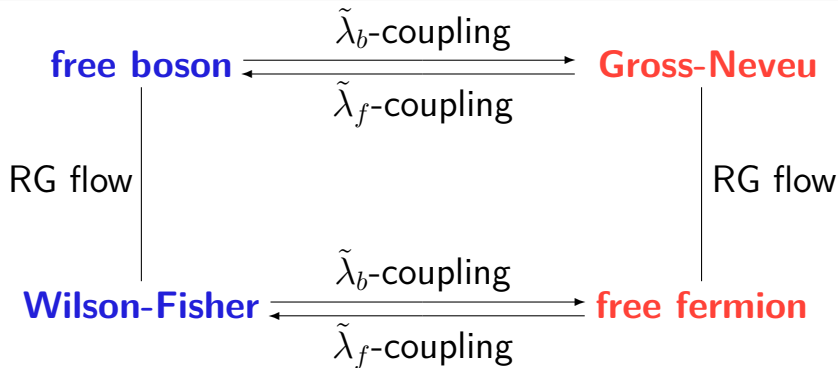
# Chern-Simons Matter Theories and bosonization duality



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

$$\frac{k}{4\pi} S_{CS}(A) + \text{Matter} \begin{cases} \int (D\phi^i)^2 & \text{free boson} \\ \int (D\phi^i)^2 + (\phi^i)^2 \sigma & \text{Wilson-Fisher} \\ \int \bar{\psi} \not{D} \psi & \text{free fermion} \\ \int \bar{\psi} \not{D} \psi + (\bar{\psi} \psi) \sigma & \text{Gross-Neveu} \end{cases}$$

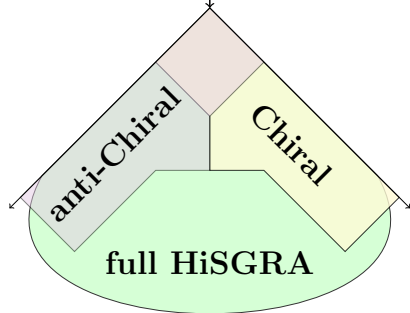
- describe physics (Ising, quantum Hall, ...)
- break parity in general (Chern-Simons)
- two parameters  $\lambda = N/k$ ,  $1/N$  ( $\lambda$  continuous for  $N$  large)
- exhibit remarkable dualities, e.g. **3d bosonization duality** (Aharony, Alday, Bissi, Giombi, Karch, Maldacena, Minwalla, Prakash,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



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

Chern-Simons Matter Theories

AdS/CFT



(anti)-Chiral Theories are rigid;  
they must be closed subsectors;

just need to glue them together to  
get all 3-pt functions in CS-Matter

gluing depends on one parameter,  
which is introduced via simple EM-  
duality rotation  $\Phi_{\pm s} \rightarrow e^{\pm i\theta} \Phi_{\pm s}$

**Bosonization is manifest!**

(anti)-Chiral Theories provide a complete base for 3-pt amplitudes

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



Maldacena, Zhiboedov found out/conjectured the  $3pt$ -functions in CS-Matter theories to be ( $\theta$  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 HiSGRA that is ahead of the CFT side**

The  $\theta$  is related to  $U(1)$  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 give two non-unitary solutions for three-point functions. What is CFT dual? (looks similar to fishnet?)**
- We can ignore the AdS-part, we are just constructing a nonlinear realization of the conformal algebra in terms of physical degrees of freedom — **Light-front bootstrap**

$$so(3,2) : \quad [T_a, T_b] = f_{ab}^c T_c \quad T_a(J_s \text{ or } \Phi_s)$$

## Concluding Remarks

- Some HiSGRA do exist, e.g. Chiral HSGRA. It reveals (almost) 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 HiSGRA is a toy model with stringy features and shows how gravity can be quantized thanks to higher spin fields: **no UV divergences, supersymmetry vs. higher spin symmetry**
- It gives all 3-pt 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
- Relation to SDYM and QCD?

Thank you for your attention!