(Quantum) Higher Spin Gravity and Physics

RTG Models of Gravity — Online Colloquium

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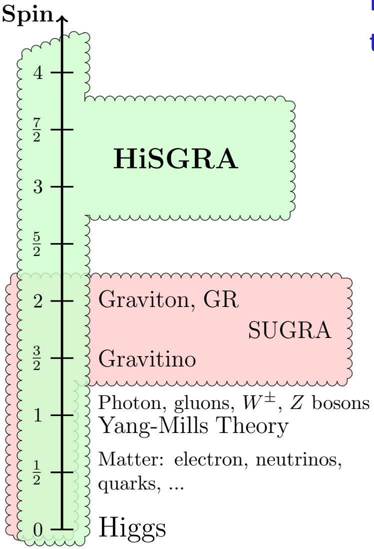
Main Messages/Teaser/Spoiler

- 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)

Plan

- 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

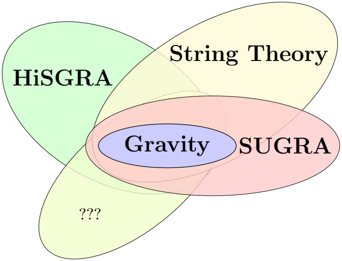
- $s = 1$: Yang-Mills, Lie algebras
- $s = 3/2$: SUGRA and supergeometry, need graviton and ...
- $s = 2$ (graviton): GR and Riemann Geometry, no color (Boulanger et al)

- $s > 2$: 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

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

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

Problem: find nonlinear completion (action, gauge symmetries)

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

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

What Higher Spin Problem is: AdS/CFT

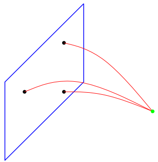
Two different ways to compute CFT correlation functions: (1) directly in CFT$_d$ and (2) as the path integral of Quantum Gravity in AdS$_{d+1}$

$$Z_{AdS} = \int \prod_i D\Phi_i\big|_{\Phi|_{\partial AdS}=A_i(x)} \exp S[\Phi]$$

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

$$\partial^m J_{ma_2\ldots a_s} = 0 \qquad \Longleftrightarrow \qquad \delta\Phi_{\mu_1\ldots\mu_s} = \nabla_{\mu_1}\xi_{\mu_2\ldots\mu_s}$$

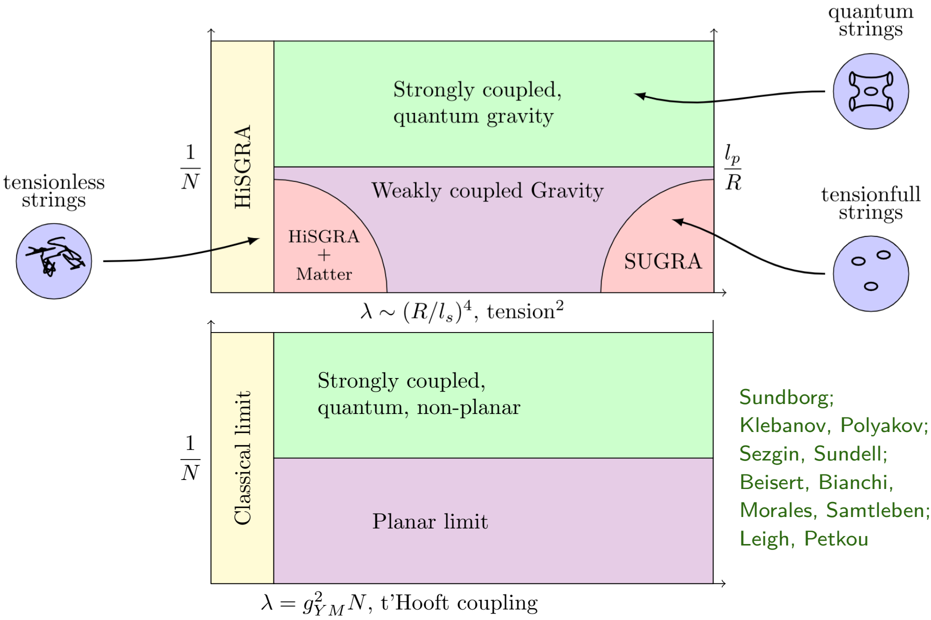
Any free CFT, e.g. free SYM, has ∞-many HS currents $J_s = \mathrm{Tr}[\phi\partial\ldots\partial\phi]$:



$$\Longleftrightarrow \qquad \langle J\ldots J\rangle \neq 0$$

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

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



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

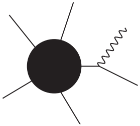
Some 'tensionless pairs'/duals of weakly-coupled CFT's

- free SYM vs. ??HiSGRA+Matter (Sundborg; Sezgin, Sundell; Beisert, Bianchi, Morales, Samtleben);
- Fishnet vs. ?? strings (Caetano, Kazakov; Gromov, Sever)
- $\mathrm{Sym}^N(\mathbb{T}^4)$ 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 in Flat space

Flat Space: HiSGRA cannot exist?

It has been long known that massless particles with $s > 2$ are somewhat special (do not want to exist). One of the most powerful no-go theorems against HiSGRA is the Weinberg low energy theorem:



- $s = 1$ we get charge conservation $\sum q_i$=0
- $s = 2$ we get equivalence principle $\sum g_i\, p^i_\mu$=0 $\rightarrow g_i = g$
- $s > 2$ we get too many conservation laws and $S = 1$,

$$\sum_i g_i\, p^i_{\mu_1} ... p^i_{\mu_{s-1}} = 0$$

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

There are many other no-go theorems, e.g. Coleman-Mandula theorem, which all sound very convincing

As a summary we can use a quote from "Quantum Field Theory and the Standard Model" by Matthew D. Schwartz

8.7.3 Spin greater than 2

One can continue this procedure for integer spin greater than 2. There exist spin-3 particles in nature, for example the ω_3 with mass of 1670 MeV, as well as spin 4, spin 5, etc. These particles are all massive. One can construct free Lagrangians for them using the same trick. An interesting and profound result is that it is impossible to have an *interacting* theory of massless particles with spin greater than 2. The required gauge invariance would be so restrictive that nothing could satisfy it. We will prove this in the next chapter. Constructing the kinetic term for a spin-3 particle is done in Problem 8.8.

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^2, 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?

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 $S \neq 1$**

Power of higher spin symmetry in AdS space

HiSGRA via symmetry restrictions

The most basic higher-spin AdS/CFT duality conjecture Klebanov, Polyakov; Sezgin, Sundell; Leigh, Petkou says that

- free vector model (fancy name for free scalars) should be dual to a higher-spin theory whose spectrum contains totally-symmetric massless fields
- critical vector model (Wilson-Fisher) should be dual to the same theory for $\Delta = 2$ boundary conditions on $\Phi(x)$. **This duality is kinematically related to the first one** (Hartman, Rastelli; Giombi, Yin; Bekaert, Joung, Mourad).

$$J_{a_1...a_s} = \phi\partial_{a_1}...\partial_{a_s}\phi \qquad \leftrightarrow \qquad \delta\Phi_{\mu_1...\mu_s}(x) = \nabla_{\mu_1}\xi_{\mu_2...\mu_s}$$

$$\langle J...J\rangle \neq 0 \qquad \leftrightarrow \qquad \text{interactions}$$

HiSGRA via symmetry restrictions

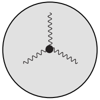
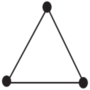
HS Current Conservation implies Free CFT, i.e. given a CFT with stress-tensor J_2 and at least one higher-spin current J_s, one can prove Maldacena, Zhiboedov; Boulanger, Ponomarev, E.S., Taronna; Alba, Diab, Stanev

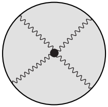
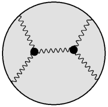
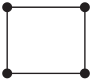
- there are infinitely many higher-spin currents and spin is unbounded;
- correlation function corresponds to free CFT (which CFT, depends on the spectrum)

This essentially proves the duality no matter how the bulk theory is realized. Loops still need to be shown to vanish (be proportional to the tree result)

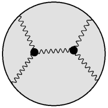
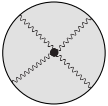
This is a generalization of the Coleman-Mandula theorem to AdS/CFT: higher spin symmetries imply free CFT, i.e. $S = 1$.

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

$\#$  $= \#$  Costa et al

 $+$  $+\, t, u =$  $= \langle JJJJ \rangle$

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

 $+\, t, u = 2\langle JJJJ \rangle$  $= -\langle JJJJ \rangle \sim \Phi^2 \frac{1}{\Box + \Lambda} \Phi^2$

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

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

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)

List of HiSGRA that survived

Quantizing Gravity via HiSGRA = Constructing Classical HiSGRA

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

Four HiSGRA in 2020

topological (Chern-Simons)	non-topological
3d conformal (Pope, Townsend; Fradkin, Linetsky; E.S., Lovrekovic, Grigoriev), $S = S_{CS}$ for HS extension of $so(3,2)$ $$S = \int \omega d\omega + \frac{2}{3}\omega^3$$	**4d conformal** (Tseytlin, Segal; Bekaert, Joung, Mourad; Adamo, Tseytlin), HS extension of Weyl gravity $$S = \int \sqrt{g}\, W^2 + ...$$
3d massless (Blencowe; Bergshoeff et al; Campoleoni, Fredenhagen, Pfenninger, Theisen; Henneaux, Rey; Gaberdiel, Gopakumar), $S = S_{CS}$ for HS extension of $sl_2 \oplus sl_2$	**4d massless chiral**, (Metsaev; Ponomarev, E.S.; Ponomarev; E.S., Tran, Tsulaia; E.S.). **This talk!**

This is the final output of the 40 years long research: the theories that 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_∞-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)
- **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)

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 flat space

$$S = \sum_s \int \Phi_{a_1\ldots a_s} \Box \Phi^{a_1\ldots a_s} \qquad\qquad \Phi_{a_1\ldots a_s} = \partial_{a_1}\xi_{a_2\ldots a_s}$$

The one-loop partition function is

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

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

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

Quantum Effects in Holographic HiSGRA

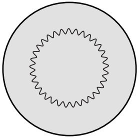
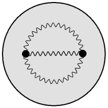
In AdS a naive cancellation is not possible

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

The one-loop partition function is

$$e^{-2F_{AdS}} = Z^2 = \frac{1}{\det \mathrm{K}_0} \frac{\det \tilde{\mathrm{K}}_0 \det \tilde{\mathrm{K}}_1 \dots}{\det \mathrm{K}_1 \det \mathrm{K}_2 \dots} =?$$

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

$$F_{AdS} = \frac{1}{G} S_{cl}[AdS] +$$

$$+\, G$$

$$+ \dots$$

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

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

The one-loop partition function is

$$e^{-2F_{AdS}}=Z^2=\frac{1}{\det \mathrm{K}_0}\frac{\det \tilde{\mathrm{K}}_0 \det \tilde{\mathrm{K}}_1 \dots}{\det \mathrm{K}_1 \det \mathrm{K}_2 \dots}=?$$

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

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

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

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

Quantum Effects in Holographic HiSGRA

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

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

ζ'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: $\boldsymbol{F^1_{AdS}} = 0$, ok we have $0 = 0$;
- for even spins: $\boldsymbol{F^1_{AdS}} = \boldsymbol{F^0_{CFT}}$, so the duality can work if $G^{-1} = N - 1$ and we have

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

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' $F^3_\phi = \frac{1}{16}(2\log 2 - \frac{3\zeta(3)}{\pi^2})$ 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

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

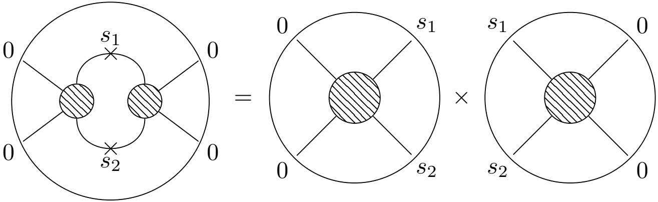
In particular, around $AdS_{4.99}/CFT^{3.99}$ for Wilson-Fisher

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

The ϵ-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

Living on Light Front

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_μ, $L_{\mu\nu}$ directly

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 $\Phi_{\pm 2}$

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

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

Chiral HSGRA in Minkowski

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

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

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

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

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

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

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

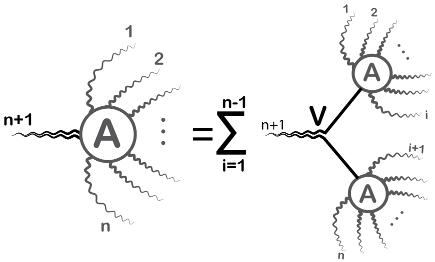
light-cone gauge is very close to the spinor-helicity language

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

The relation to SDYM is deeper than it seems (Ponomarev)

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

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

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!** 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

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

$$A^{\text{1-loop}}_{\text{Chiral}} = A^{++\ldots+}_{\text{QCD,1-loop}} \times D^{\text{HSG}}_{\lambda_1,\ldots,\lambda_n} \times \sum_{\lambda} 1$$

Chiral HSGRA in Minkowski

- **stringy 1**: the spectrum is infinite $s = 0, (1), 2, (3), 4, ...$
- **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
- **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.

Chiral HSGRA in AdS

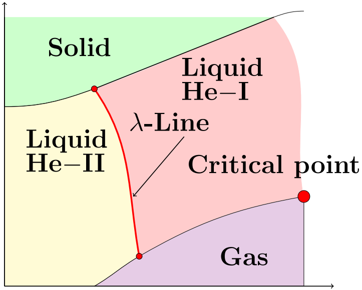
With the help of Metsaev, 2018 it is possible to uplift Chiral Theory to AdS_4. Now it is less trivial

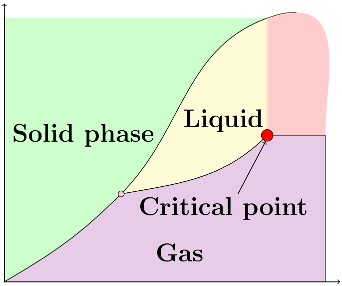
- we still have cubic action of the form

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

- 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



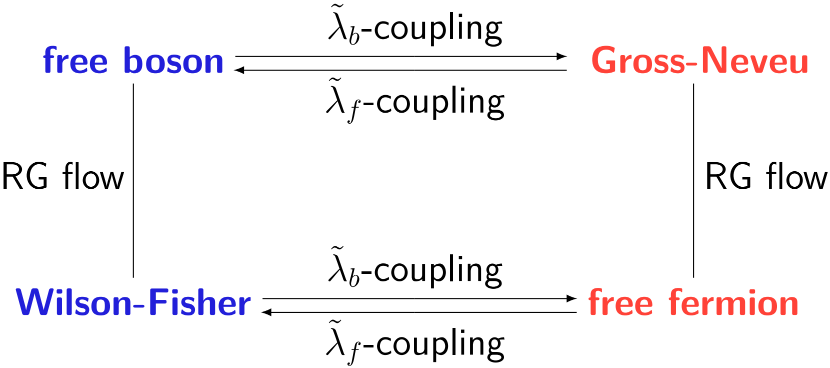


In AdS_4/CFT_3 one can do much better — there exists a large class of models, Chern-Simons Matter theories (extends to ABJ(M))

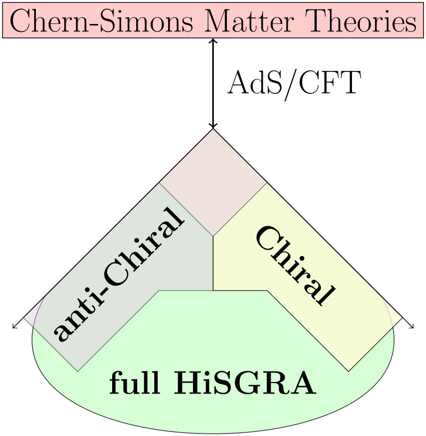
$$\frac{k}{4\pi}S_{CS}(A) + \text{Matter}\begin{cases} \int (D\phi^i)^2 & \textbf{free boson} \\ \int (D\phi^i)^2 + (\phi^i)^2\sigma & \textbf{Wilson-Fisher} \\ \int \bar{\psi}\not{D}\psi & \textbf{free fermion} \\ \int \bar{\psi}\not{D}\psi + (\bar{\psi}\psi)\sigma & \textbf{Gross-Neveu} \end{cases}$$

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

Chern-Simons Matter theories and dualities



$\gamma(J_s)$ 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 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 $\Phi_{\pm s} \to e^{\pm i\theta}\Phi_{\pm s}$

Bosonization is manifest!

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

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

Maldacena, Zhiboedov found out/conjectured the $3pt$-functions in CS-Matter theories to be (θ is related to N, k in a complicated way):

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

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 θ 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**

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

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!