Recent developments in Higher Spin Gravity

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Main Messages

- 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)
- HiSGRA have a niche within AdS/CFT as duals of (Chern-Simons) vector models, relation to $3d$ bosonization duality
- Chiral HiSGRA: action, amplitudes, UV-finiteness, SDYM/SDGR
- Higher spin symmetry as 'Virasoro' & $3d$ bosonization
- Chiral approach to massive higher spins

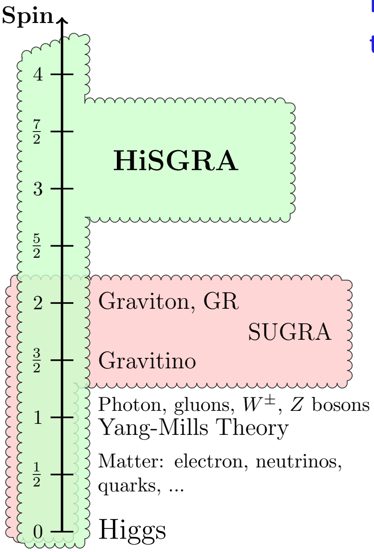
- **More:** Snowmass paper, ArXiv: 2205.01567; **even more:** lectures by Dmitry Ponomarev, ArXiv: 2206.15385

Plan/keywords

- Spin, higher spin, higher spin gravity
- Power of higher spin symmetry;
  how not to construct HiSGRA: no-go's, ...
- HiSGRA field theories in 2022
- Chiral HiSGRA: amplitudes, actions, SDYM and SDGR truncations, $3d$ bosonization duality
- Higher spin symmetry as 'new Virasoro' & 3d bosonization
- Chiral approach to massive higher spins

Everything is done with Gerasimenko, Herfray, Krasnov, Ochirov, Ponomarev, Sharapov, Sukhanov, Tran, Tsulaia, van Dongen, Yin

Spin by spin



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

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

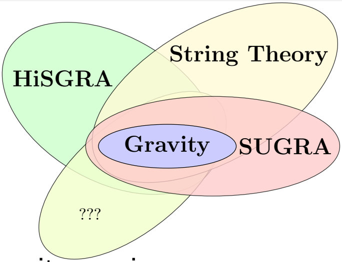
- $s = 1$: Yang-Mills, Lie algebras
- $s = 3/2$: SUGRA and supergeometry, graviton $\in$ spectrum
- $s = 2$ (graviton): GR and Riemann Geometry, no color

- $s > 2$: HiSGRA and String theory, ∞ states, 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?

(... ; Fronsdal; Berends et al; Brink, Bengtsson^2; Fradkin, Vasiliev; ...)

What Higher Spin Problem is: Field theory approach

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 $\delta A_\mu = \partial_\mu \xi, \qquad \delta g_{\mu\nu} = \nabla_\mu \xi_\nu + \nabla_\nu \xi_\mu$
Fronsdal, Berends, Burgers, Van Dam, Bengtsson^2, Brink, ...

Problem: find a 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

Warning: brute force does not seem to work! Moreover, there does not seem to be a solution along these <u>exact</u> lines ...

Power of higher spin symmetry
know your friend/enemy

too small symmetry: nothing can be computed even with a theory
too big symmetry: everything is fixed even without a theory
higher spin symmetry: almost everything is fixed and there are very few theories

Between Scylla and Charybdis

The main HS-problem is that HiSGRA do not (want to) exist, which might be related to the complexity of the quantum gravity problem

The research is heavily constrained by many no-go theorems (there are many more no-go's than yes-go's)

It is important to know the basic ones as not to look in a dark room for a black cat that isn't there

Two types of no-go's:

- **Global**: constraining (holographic) S-matrix type observables
- **Local**: constraining options for having interesting actions $\mathcal{L}[\Phi]$ or Hamiltonians

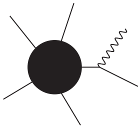
Check different space-times, e.g. **Flat** and **(anti)-de Sitter**

Higher spin symmetry constraints on S-matrix

Global & Flat: **asymptotic higher spin symmetry** in Minkowski

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

Weinberg low energy theorem (similarly, Coleman-Mandula theorem):



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

$s=1$: charge conservation; $s=2$ equivalence principle, $g_i = g$;
$s>2$ more or less imply that $S=1$ for HiSGRA. This is irrespective of whether they exist or not as local field theories.

Recent developments: distributional amplitudes (Joung, Nakach, Tseytlin; Ponomarev)

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; ...)

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

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

Possible resolutions:
(1) **Local & Flat:** there are obstructions at the quartic order (Bekaert, Boulanger, Leclerq; Roiban, Tseytlin; Taronna; Ponomarev, E.S.; ...)
(2) **there are some HiSGRA, but the interactions are fine-tuned to give $S = 1$ in Minkowski**, integrability ...

Higher spin symmetry constraints on holographic S-matrix

Global & AdS: **asymptotic higher spin symmetry** in anti-de Sitter

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

$$\Updownarrow$$

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 HiSGRA $S=$ **free CFT**

Higher spin symmetry constraints on holographic S-matrix

Global & AdS (bonus): **asymptotic slightly-broken higher spin symmetry** (Maldacena, Zhiboedov) in anti-de Sitter

$$\delta\Phi_{\mu_1\dots\mu_s}(x) = \nabla_{\mu_1}\xi_{\mu_2\dots\mu_s} \qquad \Longleftrightarrow \qquad \partial^m J_{ma_2\dots a_s} = \frac{1}{N}[JJ] \neq \mathbf{0}$$

Large-N critical vector model (Wilson-Fisher)

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

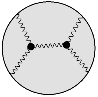
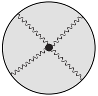
should be dual to the same HiSGRA (Klebanov, Polyakov), which is 'kinematics' (Hartman, Rastelli; Giombi, Yin; Bekaert, Joung, Mourad).

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, ...)
New input: vector models have slightly-broken higher spin symmetry!

Where Field theory cries...

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

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

Quartic vertex $\sim$ exchange. Field theory does not like that, which invalidates Noether procedure. No large gap, so as expected! (Heemskerk, Penedones, Polchinski, Sully)

(Maldacena, Zhiboedov, Simmons-Duffin): duals of vector models are closer to strings than to field theories, different from strongly coupled SYM

AdS/CFT allows one to get 'no-go' even quicker than in flat space, cf. (Bekaert, Boulanger, Leclerq; Roiban, Tseytlin; Taronna; Ponomarev, E.S.; ...) vs. ([Bekaert, Erdmenger, {Ponomarev}, (Sleight], Taronna))

Collective dipole (Jevicki et al; Aharony et al) reconstructs a theory?

S-matrix summary

We see that **asymptotic higher spin symmetries** (HSS)

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

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

$$S_{\text{HiSGRA}} = \begin{cases} 1^{***}, & \text{flat space} \\ \text{free CFT}, & \text{asymptotic AdS, unbroken HSS} \\ \textbf{Chern-Simons Matter}, & \textbf{asymptotic AdS}_4\textbf{, slightly-broken HSS} \end{cases}$$

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 ∞ spins and derivatives, invalidating the local QFT approach

HiSGRA that survived as field theories

Quantizing Gravity via HiSGRA = Constructing Classical HiSGRA

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

Four classes of local HiSGRA in 2022

3d massless, conformal and partially-massless (Blencowe; Bergshoeff, Blencowe, Stelle; Campoleoni, Fredenhagen, Pfenninger, Theisen; Henneaux, Rey; Gaberdiel, Gopakumar; Grumiller et al; Grigoriev, Mkrtchyan, E.S.; Pope, Townsend; Fradkin, Linetsky; Grigoriev, Lovrekovic, E.S.), $S = S_{CS}$ for a higher spin extension of $sl_2 \oplus sl_2$ or of $so(3,2)$

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

4d conformal (Tseytlin, Segal; Bekaert, Joung, Mourad; Adamo, Tseytlin), higher spin extension of Weyl gravity, local Weyl symmetry tames non-localities

$$S = \int \sqrt{g}\,(C_{\mu\nu,\lambda\rho})^2 + ...$$

IKKT matrix model for fuzzy H_4 (Steinacker, Sperling, Fredenhagen, Tran)

4d massless chiral (Metsaev; Ponomarev, E.S.; Ponomarev; E.S., Tran, Tsulaia; E.S.). The smallest higher spin theory with propagating fields. **This talk!**

The theories avoid all no-go's. Surprisingly, all of them have simple actions and are clearly well-defined, as close to Field Theory as possible

Chiral Higher Spin Gravity

Self-dual Theories

Chiral Theory shares a lot with self-dual theories

- actions are not real in Minkowski space
- actions are simpler than the complete theories
- integrability, instantons (Atiyah, Hitchin, Drinfeld, Manin; ...)
- **SD theories are consistent truncations**, so anything we can compute will be a legitimate observable in the full theory; **any solution of SD is a solution of the full; any amplitude is ...**
- different expansion schemes: instantons instead of flat, MHV, etc.

In general: amplitudes (MHV, BCFW, double-copy, ...), strings, QFT, Twistors, ... encourage to go outside Minkowski

In higher spins: little explored (Adamo, Hähnel, McLoughlin; E.S., Ponomarev; Ponomarev; Tran), can be the only reasonably local theories

Chiral HSGRA in Minkowski

Self-dual Yang-Mills is a useful analogy

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

$$\mathcal{L}_{\text{YM}} = \text{tr}\, F_{\mu\nu} F^{\mu\nu}$$

$$\wr\wr$$

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

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

We will do something like this to get Chiral Theory, but the completion is not known, so we proceed to the truncation of a yet unknown theory

Chiral HSGRA in Minkowski

Chiral HiSGRA (Metsaev; Ponomarev, E.S.) has fields of all spins $s = 0, 1, 2, 3, ...$:

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

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

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

Locality + Lorentz invariance + genuine higher spin interaction result in a unique completion

This is the smallest higher spin theory and it is unique.
Graviton and scalar field belong to the same multiplet

No UV Divergences! One-loop finiteness

Tree amplitudes vanish. 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, Tran). Some loop momenta eventually factor out, just as in $\mathcal{N}=4$ SYM, but ∞-many times.

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.:

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

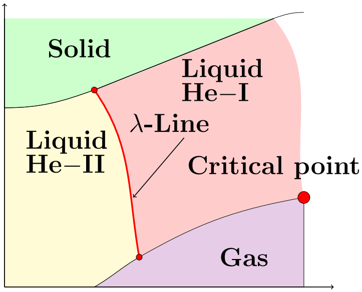
d.o.f.$= \sum_\lambda 1 = 1 + 2\sum_{\lambda>0} 1 = 1 + 2\zeta(0) = 0$ to comply with no-go's, (Beccaria, Tseytlin) and agrees with many results in AdS, where $\neq 0$

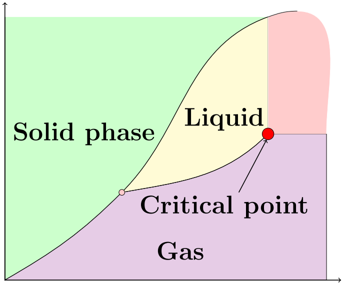
Chiral HSGRA in Minkowski

- **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

Apart from Minkowski space the theory exists also in (anti)-de Sitter space, where holographic S-matrix turns out to be nontrivial ... and related to Chern-Simons matter theories and $3d$ bosonization

Chern-Simons Matter Theories and bosonization duality





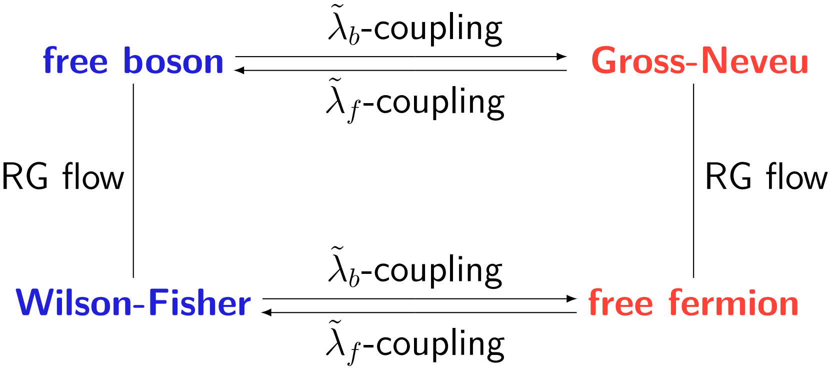
Chern-Simons Matter theories and dualities

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))

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

- 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. ***3d*** **bosonization duality** (Aharony, Alday, Bissi, Giombi, Karch, Maldacena, Minwalla, Prakash, Seiberg, Tong, Witten, Yacobi, Yin, Zhiboedov, ...)

Chern-Simons Matter theories and dualities

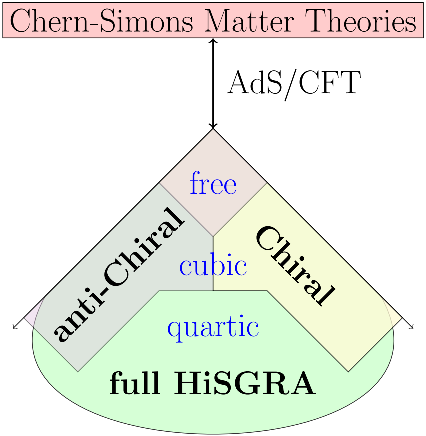


The simplest gauge-invariant operators are $J_s = \phi D...D\phi$ or $J_s = \bar{\psi}\gamma D...D\psi$, which are dual to higher spin fields.

Currents are slightly non-conserved $\partial \cdot J = \frac{1}{N}[JJ]$

$\gamma(J_s)$ at order $1/N$ (Giombi, Gurucharan, Kirillin, Prakash, E.S.) confirm the duality. Many other tests!

Chiral HiSGRA and Chern-Simons Matter



∃ Chiral HiSGRA → ∃ closed subsector

(anti)-Chiral Theories are rigid, we need to learn how to glue them

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

gives all 3-point correlators consistent with (Maldacena, Zhiboedov)

Bosonization is manifest! Concrete predictions from HiSGRA.

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

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

Covariantizing Chiral Theory SDYM and SDGR

Vector-spinor dictionary

Each $\mu = 0, ..., 3$ equals AA' where $A, B, ... = 1, 2$ and $A', B', ... = 1, 2$

$$\sigma_\mu^{AA'} v^\mu = v^{AA'} \qquad v = \begin{pmatrix} t+x & y+iz \\ y-iz & t-x \end{pmatrix}$$

In general we have $V^{A(n),A'(m)}$ and all indices are symmetric. The only anti-symmetric object is invariant $\epsilon_{AB} = -\epsilon_{BA}$, idem. for $\epsilon_{A'B'}$. Abstract Penrose notation:

$$\begin{aligned} \text{Maxwell}: &\qquad F_{\mu\nu} = F_{AB}\epsilon_{A'B'} + \epsilon_{AB}F_{A'B'} \\ \text{Weyl}: &\qquad C_{\mu\nu,\lambda\rho} = C_{ABCD}\epsilon_{A'B'}\epsilon_{C'D'} + \epsilon_{AB}\epsilon_{CD}C_{A'B'C'D'} \\ \text{Traceless}: &\qquad \Phi_{\mu(s)} = \Phi_{A(s),A'(s)} \end{aligned}$$

Any of $V^{A(n),A'(m)}$ with $n + m = 2s$ can describe a spin-s field. For $n = m = s$ we have a symmetric/Hermitian description. For $m = 2s$, $n = 2s$ we have (conjugate) Weyl tensors $\Psi^{A(2s)}$, $\Psi^{A'(2s)}$.

Twistor-inspired approach

Twistors treat positive and negative helicities differently:

$$\nabla_B{}^{A'}\,\Psi^{BA(2s-1)}=0 \qquad \text{(Penrose, 1965)}$$

$$\nabla^A{}_{B'}\,\Phi^{A(2s-1),B'}=0 \qquad \delta\Phi^{A(2s-1),B'}=\nabla^{AB'}\xi^{A(2s-2)}$$

(Hitchin, 1980) entertains a possibility to introduce a connection

$$\omega^{A(2s-2)}\ni e_{BB'}\Phi^{A(2s-2)B,B'} \qquad \delta\omega^{A(2s-2)}=\nabla\xi^{A(2s-2)}$$

where $e_{AA'}$ is the vierbein and with $H^{AB}\equiv e^A{}_{C'}\wedge e^{BC'}$ we can write

$$\boldsymbol{S=\int \Psi^{A(2s)}\wedge H_{AA}\wedge \nabla\omega_{A(2s-2)}}$$

which is also invariant under $\delta\omega^{A(2s-2)}=e^A{}_{C'}\,\eta^{A(2s-3),C'}$ to get rid of the extra component. The simplest action for HS. Admits self-dual backgrounds ...

N.B: for $s=1$ we have Ψ^{AB} and $A^{CC'}$, for $s=2$ Ψ^{ABCD} and $\Phi^{AAA,A'}$

Self-dual Yang-Mills

With $F^2_{\mu\nu} = F^2_{AB} + F^2_{A'B'}$ and with $F \wedge F = F^2_{AB} - F^2_{A'B'}$ being topological we can massage YM action

$$S_{YM} = \frac{1}{g^2} \int F^2_{\mu\nu} \sim \frac{1}{g^2} \int F^2_{AB} \sim \int \boldsymbol{\Psi^{AB} F_{AB} - \frac{g'}{2} \Psi^2_{AB}} \,,$$

which is not manifestly real! The first part is the SDYM action

$$S_{\text{SDYM}}[\Psi, \omega] = \int \Psi^{CD} F_{CD}(\omega) = \int \Psi^{CD} H_{CD} \wedge d\omega + \ldots$$

where we see the familiar action

As different from the flat space perturbation theory, we find an expansion of YM over SDYM, which is quite useful (Adamo et al; Chicherin et al; ...)

Covariantization, SDYM, SDGR

Chiral HiSGRA admits two contractions (Ponomarev) to higher spin extensions of SDYM and SDGR

These theories do not need scalar field and involve 1- and 2-derivative interactions which are not 'confining' enough

They can be covariantized (Krasnov, E.S., Tran). Firstly, we pack

$$\omega(y) = \sum_k \omega_{A_1...A_k}\, y^{A_1}...y^{A_k} \qquad\qquad \Psi(y) = ...$$

$\nabla\omega$ and H can be replaced with

$$F = d\omega + \tfrac{1}{2}[\omega, \omega]$$

where $[f, g]$ is either due to Lie algebra (HS-SDYM) or due to Poisson bracket on $\mathbb{R}^2$ (HS-SDGR, $\Lambda \neq 0$), which is the same as $w_{1+\infty}$:

$$\{f, g\} = \epsilon^{AB}\, \partial_A f(y)\, \partial_B g(y)$$

Covariantization, SDYM, SDGR

For HS-SDYM we have

$$S = \sum_n \mathrm{tr} \int \Psi^{A(2s)} H_{AA} \wedge F_{A(2s-2)}$$

For HS-SDGR in flat space we simply have

$$S = \sum_{m,n} \int \Psi^{A(n+m)}\, d\omega_{A(n)} \wedge d\omega_{A(m)}$$

For HS-SDGR with cosmological constant we need Poisson bracket in F

$$S = \sum_{m,n} \int \Psi^{A(n+m)}\, F_{A(n)} \wedge F_{A(m)}$$

The flat limit is smooth! $F = d\omega + \frac{1}{2}[\omega, \omega] \to d\omega$

For $s = 2$ we have SDGR (Plebansky; Krasnov; Hitchin; Krasnov, E.S.)

Higher spin symmetry and bosonization duality

Unbroken Higher spin symmetry

In free theories we have ∞-many conserved $J_s = \phi\partial...\partial\phi$ tensors.

Free CFT = Associative (higher spin) algebra

Conserved tensor $\rightarrow$ current $\rightarrow$ symmetry $\rightarrow$ invariants=correlators.

$$\partial \cdot J_s = 0 \quad \Longrightarrow \quad Q_s = \int J_s \quad \Longrightarrow \quad [Q,Q] = Q \quad \& \quad [Q,J] = J$$

HS-algebra (free boson) = HS-algebra (free fermion) in $3d$

Correlators are given by invariants (Sundell, Colombo; Didenko, E.S.; ...)

$$\langle J...J \rangle = \mathrm{Tr}(\Psi \star ... \star \Psi) \qquad\qquad \Psi \leftrightarrow J$$

where Ψ are coherent states representing J in the higher spin algebra

$$\langle JJJJ \rangle_{F.B.} \sim \cos(Q^2_{13} + Q^3_{24} + Q^4_{31} + Q^1_{43}) \cos(P_{12}) \cos(P_{23}) \cos(P_{34}) \cos(P_{41}) + ...$$

Slightly-broken higher spin symmetry

What is going on in Chern-Simons-matter theories?

HS-currents are responsible for their own non-conservation:

$$\partial \cdot J_s = \sum_{s_1,s_2} C_{s,s_1,s_2}(\lambda)\frac{1}{N}[J_{s_1}J_{s_2}]$$

which is an exact non-perturbative quantum equation. In the large-N we can use classical (representation theory) formulas for $[JJ]$.

The worst case $\partial \cdot J =$ some other operator. The symmetry is gone, the charges are not conserved, do not form Lie algebra.

In our case the non-conservation operator $[JJ]$ is made out of J themselves, but charges are still not conserved.

Slightly-broken Higher spin symmetry is new Virasoro?

In large-N Chern-Simons vector models (e.g. Ising) higher spin symmetry does not disappear completely (Maldacena, Zhiboedov):

$$\partial \cdot J = \frac{1}{N}[JJ] \qquad\qquad [Q,J] = J + \frac{1}{N}[JJ]$$

What is the right math? We should deform the algebra together with its action on the module, so that the currents can 'backreact':

$$\delta_\xi J = l_2(\xi, J) + l_3(\xi, J, J) + \dots\,, \qquad\qquad [\delta_{\xi_1}, \delta_{\xi_2}] = \delta_\xi\,,$$

where $\xi = l_2(\xi_1, \xi_2) + l_3(\xi_1, \xi_2, J) + \dots$. This leads to L_∞-algebra.

Correlators = invariants of L_∞-algebra and are unique (Gerasimenko, Sharapov, E.S.), **which proves $3d$ bosonization duality at least in the large-N**. Without having to compute anything one prediction is

$$\langle J \dots J \rangle = \sum \langle \text{fixed} \rangle_i \times \text{params}$$

Random comments

Random comments

HiSGRA in dS as well: prediction for R vs. R^3 corrections in cosmology, (Anninos et al,...)

Quantum checks in conformal HiSGRA and holographic (hands free) (Giombi, Klebanov, Safdi; Tseytlin; ... ; Ponomarev, Sezgin, E.S.)

Holographic HiSGRA amplitudes seem to be closer to Veneziano's (Ponomarev) and full HiSGRA dual of vector models is stringy? (Neiman)

Chiral Theory can be detected via recent celestial and twistor studies (Ren, Spradlin, Srikant, Volovich; Monteiro; Bu, Heuveline, Skinner)

At least for HS-SDYM and HS-SDGR there are analogs of Ward/Penrose theorems, likely for Chiral Theory as well (Herfray, Krasnov, E.S.)

Chiral Theory's action is Chern-Simons on twistor space? (Tran)

Covariant equations of motion (Sharapov, E.S., Sukhanov, Van Dongen), all of the ideas behind Vasiliev equations applied plus some new, also (Didenko)

Massive Higher Spins

(no no-go's, no challenge?)

Massive higher spins?

... but string's spectrum is full of massive higher spins ...

Massive higher spins are more complicated (Fierz, Pauli): 2nd class constraints, Boulware-Deser ghosts, actions are not easy (Singh, Hagen; Zinoviev)

$$(\Box - m^2)\Phi_{\mu_1\ldots\mu_s} = 0 \qquad\qquad \partial^\nu \Phi_{\nu\mu_2\ldots\mu_s} = 0$$

Low spins: $s = 1$ spontaneously broken Yang-Mills; $\boldsymbol{s = 3/2}$; $s = 2$ massive (bi)-gravity (dRGT; Hassan, Rosen)

Simple idea in $4d$ (Ochirov, E.S.): instead of $\Phi_{A(s),A'(s)}$, i.e. (s, s) of $sl(2, \mathbb{C})$ we suggest chiral description $\Phi_{A_1\ldots A_{2s}}$, i.e. $(2s, 0)$. Parity is not easy ...

Easy to introduce EM, YM and gravitational interactions, all-helicity-plus amplitudes are reproduced; relation to black-hole scattering (Arkani-Hamed, Huang^2; Guevara, Ochirov, Vines). Of course, these are effective field theories ... but everything small and rotating is a higher spin particle from a distance

Summary and Comments

- Chiral HiSGRA is a toy model with stringy features and shows how higher spin fields improve the UV behaviour: **no UV divergences, supersymmetry vs. higher spin symmetry**
- It gives all 3-pt functions in Chern-Simons Matter theories, making new predictions and proves the bosonization duality to this order.
- Higher spin symmetry itself: proof of $3d$ bosonization duality in the large-N. L_∞-algebras in physics
- Anomalous dimensions of HS-currents are small even for Ising model, $N = 1$, e.g. $\Delta(J_4) = 5.02$ instead of 5
- Chiral Theory is dual to a closed subsector of vector models. How to find it? Extension to small N due to integrability, Ising?
- **Optimistically: HiSGRA can give viable quantum gravity models not free of direct applications to physics**

Thank you for your attention!

may the higher spin force be with you!

... there is more Chiral ...