What Can We Learn From Coset CFTs and Their Duals

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What We Don't Know (in AdS/CFT)?

In our best understood example of $\mathcal{N} = 4$ SYM, we now know (in principle) the spectrum of all single trace operators (at $N = \infty$) for all λ $\leftrightarrow$ perturbative string states.

But we still do not know:

- The spectrum at finite N (for generic λ). Relevant to understanding the physics of black holes and other geometries in AdS_5.
- Correlation functions of arbitrary operators (just for single trace operators) and even at the planar level (for generic λ). Presumably will see progress using integrability techniques.
- Even the spectrum of perturbative string states has no independent derivation yet from the string side apart from at large λ.

Clearly, a lot of work for us to do !

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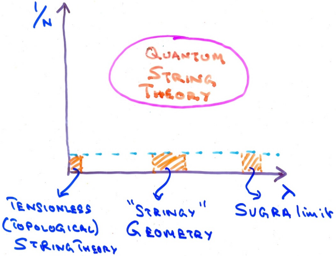
Information Imbalance

- Gravity $\to$ ($\lambda \gg 1$) Gauge Theory : Lots of Amazing Results.
- Gauge theory $\to$ (Stringy/Quantum) Gravity: A Lot Less.



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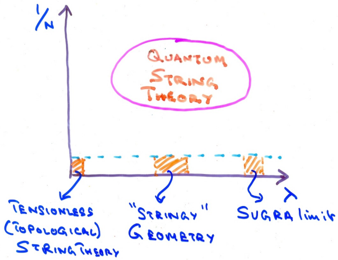

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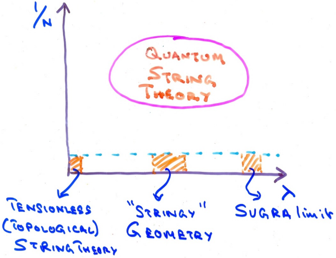

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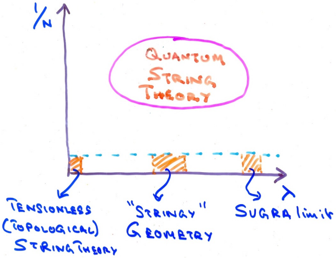

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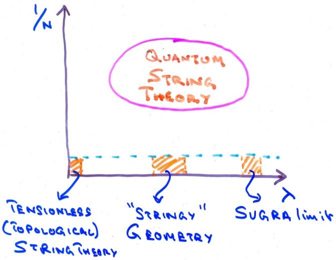

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What Do We Need to Decipher Stringy/Quantum Geometry?

- A tractable CFT with a well defined expansion around a large N limit. Good to have a parameter (λ) which controls "stringiness".
- A bulk theory whose classical limit ($N \to \infty$) is under reasonable control. A rich set of non-trivial classical solutions (and their gravitational interpretation).

- Compare the classical solutions with boundary description. Understand what stringy features translate into in the boundary language. (Entropy of thermal states, singularity resolution, locality)
- Use the boundary CFT at finite N to learn about quantum modifications (recovery of information).

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Duals to 2d Coset CFTs: A Good Laboratory

Boundary 2d CFT

- $\frac{G}{H}$ WZW theories are solvable. There is an intricate spectrum (for any N) and correlators computable. As a bonus, non-supersymmetric.
- Presence of a large unbroken higher spin symmetry ($\mathcal{W}_N$ or often much larger).

Bulk AdS_3

- Higher spin gauge fields ($s = 2, 3 \ldots$) in AdS_3 are non-propagating (though can have propagating scalars/fermions).
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Two kinds of Coset Dualities

Vector-Like Cosets: Central charge $c \propto N$. For example $\mathcal{W}_N$ minimal models

$$\frac{SU(N)_k \times SU(N)_1}{SU(N)_{k+1}}.$$

Take $k, N \to \infty$ with ratio fixed. (Gaberdiel and R. G.)

Matrix-Like Cosets: Central charge $c \propto N^2$. For example, extended $\mathcal{W}_N$ models

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Vector Coset Holography

The CFT: Minimal $\mathcal{W}_N$ series (generalising the Virasoro unitary series for $N = 2$)

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A line of fixed points when $k, N \to \infty$ (labelled by 'tHooft coupling $0 \leq \lambda = \frac{N}{N+k} \leq 1$) with $c_N(\lambda) = N(1 - \lambda^2)$.

The Bulk: Vasiliev higher spin theory in AdS_3 with gauge group $hs[\lambda]$ coupled to one complex scalar of mass

$$M^2 = -1 + \lambda^2.$$

Central charge $c = \frac{3R_{AdS}}{2G_N}$ (Campoleoni et.al., Henneaux-Rey) i.e. $G_N \propto \frac{1}{N}$.

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What we know about the Duality

- *Matching symmetries*: Underlying $\mathcal{W}_\infty[\lambda]$ symmetry. At finite N, (i.e. finite c) both sides have $\mathcal{W}_N$ symmetry - due to a nontrivial equivalence of the quantum $\mathcal{W}_\infty[\lambda]$ symmetry algebra (Gaberdiel-R.G.). Powerful non-linear symmetry.
- *Matching Spectrum*:
  a) Perturbative excitations. (Gaberdiel-R.G.-Hartman-Raju)
  b) Non-perturbative excitations ("conical defects") (Castro-R.G.-Gutperle-Raeymakers; Perlmutter, Prochazka, Raeymakers).
  c) Black Hole States. (Kraus-Perlmutter, Gaberdiel-Hartman-Jin)
- *Correlation functions*: Matching of three point functions of scalars and currents. Large N factorisation of multi-trace operators (Chang-Yin, Kraus-Perlmutter, Papadodimas-Raju).
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- Can be generalized to other 2d vector cosets with $SO(N)$ (Ahn, Gaberdiel-Vollenweider)
- $\mathcal{N} = 1, 2$ Kazama-Suzuki models (Creutzig-Hikida-Ronne).

Analogue of 3d/4d proposal relating vector models (in general with Chern-Simons interactions) to higher spin theories on AdS_4. (Klebanov-Polyakov; Sezgin-Sundell; Giombi-Yin ; GMPTWY; Aharony et.al.)
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Classification of Bulk Solutions

Let's look at known classical bulk solutions and their boundary interpretation. In increasing order of complexity they are:

- Perturbative quanta of the bulk higher spin fields and the scalar (Gaberdiel-R. G.-Saha; Gaberdiel-R.G.-Hartman-Raju). [In SUSY case (Creutzig-Hikida-Ronne, Candu-Gaberdiel)].
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The Perturbative Bulk Spectrum

$$Z_{\mathrm{bulk}} = Z_{class} Z_{1-loop} = (q\bar{q})^{-c/24} Z_{\mathrm{HS}} Z_{\mathrm{scal}}(h)^2.$$

$$Z_{HS} = \prod_{s=2}^{\infty} \prod_{n=s}^{\infty} \frac{1}{|1-q^n|^2} = \prod_{n=1}^{\infty} |1-q^n|^2 \times \prod_{n=1}^{\infty} \frac{1}{|(1-q^n)^n|^2} \equiv |\tilde{M}(q)|^2.$$

Bulk one loop determinants of higher spin fields (Gaberdiel-R. G.-Saha).

$$Z_{scal}(h) = \prod_{l=0,l'=0}^{\infty} \frac{1}{(1-q^{h+l}\bar{q}^{h+l'})}. \tag{1}$$

Determinant of scalar - dual to operator of dim. $h = \frac{1}{2}(1+\lambda)$.
(Giombi-Maloney-Yin)

- Z_{HS} matches with the CFT spectrum of the vacuum and its descendants in the large N 'tHooft limit.
- $Z_{scal}(h)^2$ matches with that of the CFT primaries $(\Lambda_+; 0)$ and descendants where Λ_+ is an $SU(N)$ rep. built from finite tensor powers of fundamental and antifundamental. (GGHR)
- Quite nontrivial that these CFT primaries behave like single and multi-particle states i.e. correlators obey large N factorisation. (Pappadodimas-Raju; Chang-Yin).
- However, these by themselves do not give a modular invariant spectrum nor account for all the operators of dimension of order one.
- Whole families of other states - some forming a continuum down to zero ("light states") - many of which also obey large N factorisation.
- QUESTION: What do these "non-perturbative" states correspond to in the bulk?

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- However, these by themselves do not give a modular invariant spectrum nor account for all the operators of dimension of order one.
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Conical Defect Solutions

- Candidates for the dual of non-perturbative states.
- But interesting solutions of the bulk equations of motion in their own right. Found in $hs[\lambda = N] = SL(N)$ Chern-Simons theories with no scalar field turned on. Exist only for $N > 2$. (CGGR).
- Given by flat connections with holonomy in the spatial circle lying in non-trivial central elements of $SL(N)$ (since gauge group is $SL(N, \mathbb{C})/\mathbb{Z}_N$).

$$W_\phi = P \exp i \oint_\phi A \in \mathbb{Z}_N.$$

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Analytic Continuation in c (fixed N)

The Bulk: $SL(N)$ semi-classical Vasiliev theories with symmetry $\mathcal{W}_\infty[\lambda = N, c \to \infty] \longrightarrow hs[\lambda]$ Vasiliev theories with finite central charge and symmetry $\mathcal{W}_\infty[\lambda = N, c = c_{N,k}] = \mathcal{W}_\infty[\lambda = \frac{N}{N+k}, c = c_{N,k}]$.
The CFT: *Non-unitary* $\mathcal{W}_N$ CFTs (Toda theories) with large $c \longrightarrow$ Unitary $\mathcal{W}_{N,k}$ minimal models with $c = c_{N,k}$.

- Primary representations (Λ_+, Λ_-) continue to exist even when c takes non-unitary values. Seems to be a sensible analytic continuation.
- The conical defect solutions have exactly the same quantum numbers as (Λ_+, Λ_-) states in the CFT under continuation $c \to \infty$ - semi-classical limit.

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- Can also study scalars coupled to the $SL(N)$ Vasiliev theory (Perlmutter, Prochazka, Raeymakers). Now there is a band of solutions with energy splitting of order one (compared to the order c reference energy).
- From an analysis of null states, led to identify $(0, \Lambda_-)$ with pure conical defect solution - topmost in the band.
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- $$Z_{\Lambda_-} = \sum_{\Lambda_+} |b_{(\Lambda_+,\Lambda_-)}(q)|^2.$$
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- Pure $SL(3)$ higher spin theories have solutions (flat connections) of the form (Gutperle-Kraus, Ammon et.al., Castro et.al.)

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\begin{aligned}
a &= (L_1 - \frac{2\pi}{k}\mathcal{L}L_{-1} - \frac{\pi}{2k}\mathcal{W}W_{-2})dz \\
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Here $\mathcal{L}, \mathcal{W}$ are the spin two and spin three charge and μ the chemical potential for $\mathcal{W}$. Reduces to BTZ when $\mathcal{W} = 0$.

- Demand the smoothness of geometry by requiring holonomy W_t in the time direction (contractible) to be trivial and equal to that for BTZ.
- Gives two relations between $\mathcal{L}, \mathcal{W}, \beta$ and μ. Then obeys first law of thermodynamics. Also $\frac{\partial \mathcal{L}}{\partial \mu} = \frac{\partial \mathcal{W}}{\partial \beta} \Rightarrow Z(\beta, \mu)$ exists.

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- Despite there being no horizon in this gauge ! Wormhole like solution. Another gauge in which horizon exists.
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$$\ln Z_{BH}(\tau = \frac{i\beta}{2\pi}, \mu) = \frac{ic\pi}{12\tau}[1 - \frac{4\mu^2}{3\tau^4} + \frac{400}{27}\frac{\lambda^2 - 7}{\lambda^2 - 4}\frac{\mu^4}{\tau^8} - \frac{1600}{27}\frac{5\lambda^4 - 85\lambda^2 + 377}{(\lambda^2 - 4)^2}\frac{\mu^6}{\tau^{12}} + \ldots].$$

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$$\begin{aligned}\ln Z_{BH}(\tau = \frac{i\beta}{2\pi}, \mu) &= \frac{ic\pi}{12\tau}[1 - \frac{4\mu^2}{3\tau^4} + \frac{400}{27}\frac{\lambda^2 - 7}{\lambda^2 - 4}\frac{\mu^4}{\tau^8} \\ &- \frac{1600}{27}\frac{5\lambda^4 - 85\lambda^2 + 377}{(\lambda^2 - 4)^2}\frac{\mu^6}{\tau^{12}} + \ldots].\end{aligned}$$

- Matches with CFT answer at very large temperatures - to this order in μ expansion for generic λ (Kraus-Perlmutter, Gaberdiel-Hartman-Jin).
- Nontrivial check of duality with CFT and its ability to reproduce black holes. Black hole states dominate the entropy as $T \to \infty$.
- However, at small λ no signature of a Hawking-Page transition (Banerjee et.al.). More detailed analysis being carried out at generic λ (Gaberdiel-R.G.-Rangamani).

Matrix Cosets

- Can generalize the vector cosets to

$$\frac{SU(N)_k \times SU(N)_\ell}{SU(N)_{k+\ell}}.$$

If we keep ℓ finite as $k, N \to \infty$ then we have essentially ℓ flavors of the original theory.

- When ℓ, k, N go to ∞ with ratios fixed then $c \propto N^2$ - matrix like theory.
- Now many more conserved higher spin currents (for a given spin s) than in the $\mathcal{W}_N$ minimal models.
- Much bigger gauge symmetry in the dual theory than in the Vasiliev theory - like a string theory.
- Cf. recent work by Chang-Minwalla-Sharma-Yin of embedding SUSY Vasiliev theories in ABJ string theories.

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Strange Metals in 2d

- An interesting special case is when $k = \ell = N$ (R.G.-Hashimoto-Klebanov-Sachdev-Schoutens) with $c = \frac{N^2-1}{3}$.
- Arises as IR description of two majorana fermions (in adjoint rep.) coupled to $SU(N)$ gauge field. (In turn describes the high density limit of 2d Dirac fermion coupled to gauge field - linearise about the Fermi surface). Interacting CFT - 2d analogue of strange metal.
- Interesting feature is the emergent $\mathcal{N} = (2, 2)$ SUSY - not present in the microscopic theory.
- Partial analysis of modular invariant spectrum. Find operator dimension of density $Tr(\psi^\dagger \psi)$ to be $\frac{1}{3}$ for all N. Similarly pair operator also has $\Delta = \frac{1}{3}$. Quartic relevant operators with $\Delta = \frac{2(N-2)}{3N}$.
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Questions for the Bulk

- What is the temperature regime in which black hole states dominate the thermodynamics? Make a detailed identification of the CFT microstates ($h \propto N^{\alpha}$) which contribute to BH entropy. Note the unusual thermodynamics of CFT states (Banerjee et.al.) - $F \propto NT \ln \frac{T}{\lambda^2}$ for small λ .
- Need to also study more solutions of the bulk $hs[\lambda]$ theory. Black hole solutions with scalar field nonzero. Those corresponding to different thermodynamic branches (David et.al).
- Take the large N limit of the torus 2-pt. function and see whether there is thermal decay at intermediate times much less than Poincare time ($\propto N$) (Chang-Yin). Note that at finite N there are only $2(N-1)$ mutually commuting charges.

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- Is there a quantization of the $hs[\lambda]$ Vasiliev theory which preserves the quantum $\mathcal{W}_\infty[\lambda] \to \mathcal{W}_N$ symmetry? Note that we have a "Stringy exclusion principle" at finite N (there is now a $s_{max} = N$).
- Can we prove the duality in some way? Exploit the power of the non-linear $\mathcal{W}_\infty[\lambda]$.
- Generalise the duality to other modular invariants (non-diagonal modular invariants) of the CFT. There is a large number of them - what do they correspond to in the Vasiliev theory?
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Questions for general large N 2d QFTs

Opens up the possibility to study holographic duals of solved large N 2d QFTs (generically massive).
Integrate these theories into the framework of gauge-string dualities and gain a general understanding of the domain of applicability of these ideas.
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In particular, one can envisage an increasing order of complexity of models:

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