# Thoughts on Future Landscapes

Frederik Denef

Dec 2, 2017
String Data Workshop
Northeastern University

# Outline

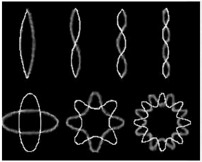
String Landscape: Feats, Failures and Future

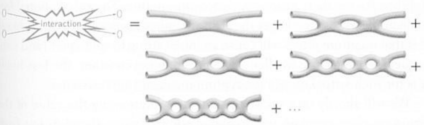
HSdSH Landscape at Future Infinity

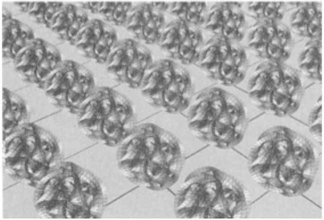
Future Machines and the Landscape of Knowledge

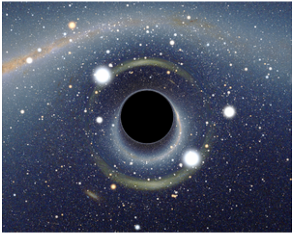
# String Landscape: Feats, Failures and Future

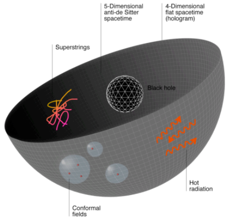
# String Theory



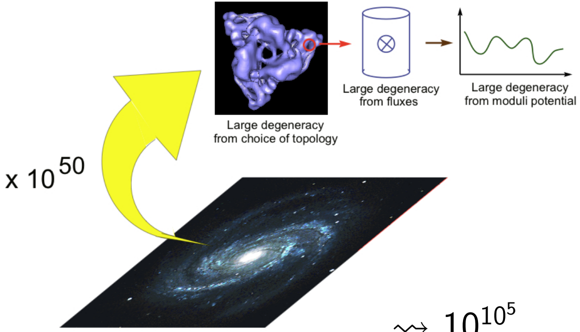


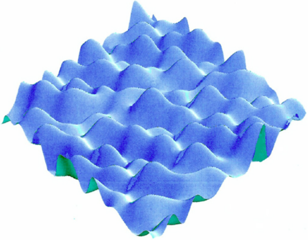




# Landscape




$\rightsquigarrow 10^{10^5}$



Many results, rich structure, exciting progress: see all other talks.

# Thirty years ago...

Although much work remains to be done there seem to be no insuperable obstacles to deriving all of known physics from the $E_8 \times E_8$ heterotic string.

[Gross, Harvey, Martinec and Rohm '85]

The focus of this paper has been the mathematical properties of superstrings in torsion backgrounds, but we would like to conclude with comments on some physical implications. With the inclusion of non-zero torsion, the class of supersymmetric superstring compactifications has been enormously enlarged. It is barely conceivable that all zero-torsion solutions could be classified, and that the phenomenologically acceptable ones (at string tree level) might then be a very small number, possibly zero. It does *not* seem likely that non-zero torsion solutions, or even just the subset of phenomenologically acceptable ones, can be classified in the foreseeable future. As the constraints on non-zero torsion solutions are relatively weak, it *does* seem likely that a number of phenomenologically acceptable (at string tree level!) ones can be found. Indeed, it is argued in [16] that some of the generic problems of the zero-torsion solutions are likely to be absent in many non-zero torsion solutions. While this is quite reassuring, in some sense life has been made too easy. All predictive power seems to have been lost.

All of this points to the overwhelming need to find a dynamical principle for determining the ground state, which now appears more imperative than ever.

[Strominger '86]

## Incompleteness Problem

- Construction of string vacua uses 10D low energy effective theory derived from string worldsheet perturbation theory.
- $\Rightarrow$ Asymptotic expansion in $g_s$ and $\ell_s$ $\Rightarrow$ incomplete.
- Some nonpert. corrections $\sim e^{-\#/g_s}, e^{-\#/\ell_s^2}$ known, but no systematic derivation from fundamental theory (in contrast to QFT).
- String theory is only a complete theory in AdS. Very different formulation (AdS-CFT). Does not remotely resemble our universe.

## Other (related) problems

- Dine-Seiberg Problem: *When corrections can be computed, they are not important, and when they are important, they cannot be computed.*
- Measure Problem: *Whenever a landscape measure is strongly predictive, it is wrong, and when it's not, we don't know if it's right.*
- Tractability Problem: *Whenever a low energy property is selective enough to single out a few vacua, finding these vacua is intractable.*

## Future

- Enumerating all possible shapes of ice crystals is an interesting but difficult problem. It is not, however, the most efficient way of inferring the properties of water vapor.

- Presumably (let's hope so!) there exists a fundamental theory of cosmology, the landscape, eternal inflation, etc, i.e. a fundamental description of the "Hilbert Space of Everything". But it surely will not look like the low energy effective descriptions currently in use.

- It may look a lot simpler!

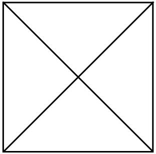
# HSdSH Landscape at Future Infinity

Anninos, Denef, Monten and Sun: arXiv:1711.10037

## Free higher spin fields de Sitter space

dS$_4$, units $\ell_{\mathrm{dS}} = 1$:

$$ds^2 = \frac{-d\eta^2 + \eta^2}{\eta^2}$$



Free conformally coupled scalar in momentum space:

$$\begin{aligned}\phi(\eta, k) &= \alpha(k)\,\eta\cos(k\eta) + \tilde{\beta}(k)\,\eta\sin(k\eta)\\ &\to \alpha(k)\,\eta + k\,\tilde{\beta}(k)\,\eta^2 \qquad (\eta \to 0)\end{aligned}$$

Local $\beta(k) = k\tilde{\beta}(k)$. (CFT *shadow transform*; $\tilde{\beta}(x) = \int d^3y\,\frac{1}{|x-y|^2}\beta(y)$.)

Free massless spin-$s$ fields:

$$\phi_{i_1\cdots i_s}(\eta, k) \to \alpha_{i_1\cdots i_s}(k)\,\eta + k^{1-2s}\tilde{\beta}_{i_1\cdots i_s}(k)\,\eta^{2-2s}$$

Local $\beta_{i_1\cdots i_s}(k) = k^{1-2s}\tilde{\beta}_{i_1\cdots i_s}(k)$.

# Perturbative bulk Hilbert space

Free field quantization:

$$\text{scalar:} \qquad [\alpha_k, \alpha_{k'}] = 0 = [\tilde{\beta}_k, \tilde{\beta}_{k'}] \,, \qquad [\tilde{\beta}_k, \alpha_{k'}] = \frac{i}{k}\, \delta_{k+k'}$$

$$\text{general spin:} \qquad [\alpha_I, \alpha_J] = 0 = [\tilde{\beta}_I, \tilde{\beta}_J] \,, \qquad [\tilde{\beta}_I, \alpha_J] = i\, G_{IJ} \,.$$

Labels $I, J$ lump together spin indices and (momentum) space points.

Free vacuum: $(\tilde{\beta}_I + i\alpha_I)|0\rangle = 0\,.$

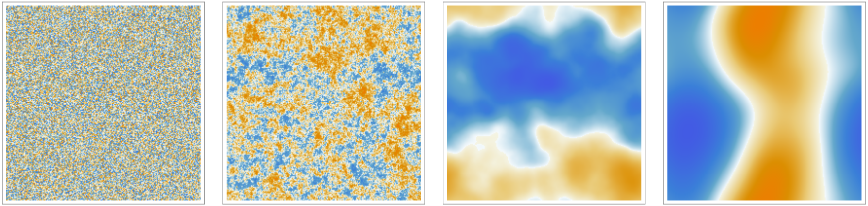
Vacuum 2-pt functions:

$$\langle 0|\tilde{\beta}_I \tilde{\beta}_J|0\rangle = \frac{1}{2} G_{IJ} = \langle 0|\alpha_I \alpha_J|0\rangle \qquad \langle 0|\tilde{\beta}_I \alpha_J|0\rangle = \frac{i}{2} G_{IJ} = -\langle 0|\alpha_J \tilde{\beta}_I|0\rangle \,.$$

Fock space $\mathscr{H}_{\rm Fock}$: $|I_1 \cdots I_n\rangle \equiv \, :\tilde{\beta}_{I_1} \cdots \tilde{\beta}_{I_n}: |0\rangle\,.$

Physical Fock space $\mathscr{H}_{\rm Fock,phys}$: $\mathcal{G}$-invariant subspace of $\mathscr{H}_{\rm Fock}$,
$\mathcal{G}$ = dS isometry group SO(1,4) + higher spin extension.

# Free higher spin "CMB"



$s = 0$ $s = 2$ $s = 4$ $s = 6$

Samples of free higher spin fields $\beta^{(s)}(x)$

$$\langle 0 | \beta_k^{(s)} \beta_{k'}^{(s)} | 0 \rangle \propto k^{1-2s} \, \delta_{k+k'}$$

## Interacting bulk theory: Minimal Vasiliev higher spin gravity

Infinitely many fields with infinitely many interaction vertices of arbitrarily high order in fields and derivatives.

- Incompleteness problem: obvious
- Dine-Seiberg problem: extreme.
- Measure problem: hopeless.
- Intractability problem: almost nothing is tractable.

and yet...

## Microscopic Hilbert space: Q-model

[Anninos-Denef-Monten-Sun]

- Fundamental degrees of freedom: $2N$ scalar fields $Q_x^\alpha$, $\alpha = 1, \ldots, 2N$, $x \in \mathbb{R}^3$. Here $N \sim$ dS entropy $\sim \ell_{\rm dS}^2 / G_{\rm Newt}$.
- $\mathscr{H}_0$: wave functions $\psi(Q)$ with standard inner product

$$\langle \psi_1 | \psi_2 \rangle = \int dQ \, \psi_1(Q)^* \, \psi_2(Q)$$

- Vacuum state:

$$\psi_0(Q) = e^{-\frac{1}{2} \int Q^\alpha \mathcal{D} Q^\alpha} , \qquad \mathcal{D} = -\nabla^2 .$$

- Symmetries: O(2N) and $\mathcal{G}$: $Q_x \to R_x{}^y Q_y$ such that $R^T \mathcal{D} R = \mathcal{D}$. $\mathcal{G} =$ Higher spin symmetry group.
- $\mathscr{H}$: O(2N)-invariant subspace of $\mathscr{H}_0$.
- $\mathscr{H}_{\rm phys}$: $\mathcal{G}$-invariant subspace of $\mathscr{H}$.

## Dictionary: dS - Q-model correspondence

Identification $\tilde{\beta}_I$ with single-trace primaries:

scalar: $\tilde{\beta}(x) = B(x) \equiv \frac{1}{\sqrt{N}} :\sum_\alpha Q_x^\alpha Q_x^\alpha:$

gravition: $\tilde{\beta}_{ij}(x) = B_{ij}(x) \equiv \frac{1}{\sqrt{N}} :Q_x \partial_i \partial_j Q - 3\partial_i Q \partial_j Q + \delta_{ij}(\partial Q)^2:$

general spin: $\tilde{\beta}_I = B_I \equiv \frac{1}{\sqrt{N}} :Q \mathcal{D}_I Q: \, .$

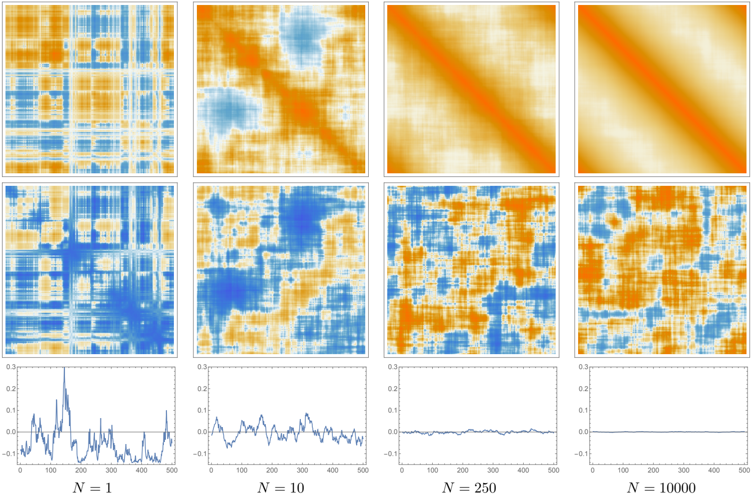
Correlation functions in Vasiliev bulk Hartle-Hawking vacuum $|\psi_{\mathrm{HH}}\rangle$

$$\langle \psi_{\mathrm{HH}} | \tilde{\beta}_{I_1} \cdots \tilde{\beta}_{I_n} | \psi_{\mathrm{HH}} \rangle = \langle \psi_0 | B_{I_1} \cdots B_{I_n} | \psi_0 \rangle$$

$\rightsquigarrow$ explicit, *exact* results for 3- and 4-point (!) functions.

Consistent with higher spin dS-CFT Sp(N) model of [Anninos-Hartman-Strominger] but going well beyond this in conceptual scope and computational power.

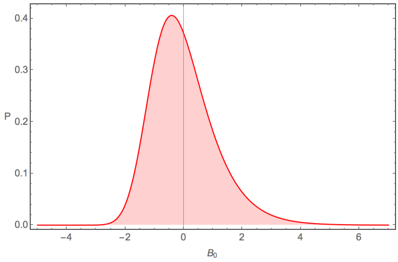
# Sampling the Vasiliev Landscape



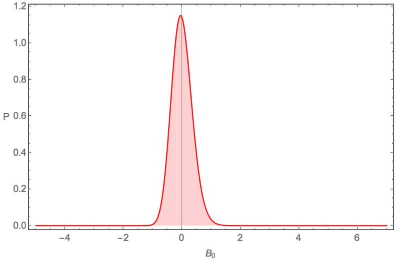

$d = 1$ model. Row 1: $H_{xy} = Q^\alpha_x Q^\alpha_y$. Row 2: $B_{xy} =: Q^\alpha_x Q^\alpha_y :$. Row 3: $B(x) = Q^\alpha_x Q^\alpha_x$.

Note the strong non-Gaussianities at small $N$.

# Probabilities for arbitrarily large field excursions




$N = 2$




$N = 20$

Probability $P(B_0)$ for constant scalar mode on global de Sitter $S^3$.

## Other results

- Reconstruction of perturbative bulk QFT canonical commutation relations $[\tilde{\beta}_J, \alpha_I] = i\, G_{IJ}$ on $\mathscr{H}$ possible, but only
  - up to minimal error term $\sim e^{-\mathcal{O}(N)}$
  - if operators coarse grained to effectively $< \mathcal{O}(N)$ spatial "pixels".
- $\mathcal{G}$-invariant $\mathscr{H}_{\text{phys}}$ quasi-topological: finite number of $n$-particle states; all $\mathcal{G}$-invariant quantities computed by $2N \times 2N$ matrix model $\rightsquigarrow$ $2N$ physical degrees of freedom.
- Suggests concrete realization of the idea of cosmological complementarity.

## Upshot

Vastly simpler and computational powerful exact microscopic description of quantum cosmology is possible, even though low energy effective field theory was horrifically complicated!

The fantasy here is is that one day, we will have a similarly simple (though perhaps not *that* simple) description of realistic landscapes capable of generating all known physics without insuperable obstacles. This theory may or may not have anything in common with string theory.

Perhaps it would be wise, therefore, to develop AI / Machine Learning / Data Science applications in such a way that they are not tied specifically to our current favorite descriptions of physics. With flexible, general-purpose, newbie-friendly AI tools, future generations of young theorists are bound to get creative in as yet unanticipated directions.

In the following I'll veer a little bit off-workshop-topic and give an example of a potentially field-revolutionizing AI meta-application transcending any specific topic.

# Future Machines and the Landscape of Knowledge

## Some facts

Source: *"The STM Report"* [Ware and Mable, 2015]:

- 50-100 million scientific articles published since 1665.
- Currently $\sim$ 3 million/year
- Rate doubles every 20 years (over almost entire span of 350 years).
  $\Rightarrow \sim$ 100 million/year by 2117.
- Google Scholar: 300,000 hits on "string theory".
- *"The Large N limit of superconformal field theories and supergravity"* [Maldacena '97] has spawned 15,000 research articles, but only 1 comprehensive review paper, 18 years old [MAGOO '99].
- No human can absorb even a tiny fraction of this runaway torrent.

The good news is:

- Moore's law beats this by a factor of 10 in the exponent:
  # transistors / chip doubles every 2 years.
  $\Rightarrow$ Machines should be able to catch up soon!

## Robot Readers

For obvious reasons, besides time constraints, incentives to write papers are much stronger for research scientists than to read them. So printed stacks pile up unread, PDFs remain ambitiously open until we reboot our laptops, recursive reference-backtracking gets sidetracked by the deluge of micro-distractions puncturing our days. This, plus the sheer volume of disorganized pages of important results, leads to loss of access to crucial knowledge, to repeated duplication of efforts, and to many other inefficiencies. Worst of all, it becomes increasingly harder for young brilliant minds to stand on the shoulders of giants, and thus to make revolutionary new discoveries.

It seems inevitable that we will have to outsource the tedious task of parsing the literature, in search for relevant results, insights, questions and inspiration, to the Machines.

## Machine Learning and the arXiv

Sources:

- Blog "Quantum Frontiers", [Evert van Nieuwenburg], Nov 29, 2017.
- [Mikolov, Chen, Corrado, and Dean: arXiv:1301.3781, 1310.4546]

"Words to Vectors" machine learning algorithm. [arXiv:1301.3781]: Neural network reads text, 1.6 billion words in 1 day, organizes them in vector space of meanings and associations. [arXiv:1310.4546]: generalization to phrases.

After training, it can compute things like:

- King - Man + Woman = Queen
- Paris - France + Italy = Rome

Van Nieuwenburg applied this "words to vectors" algorithm to just the titles of the cond-mat arXiv. Already got things like

- 2d + electrons + magnetic field = Landau level

Evidently potentially powerful tool for mining the literature!

## Roadmap

- Formula search.
- Concept search.
- Background literature recommendations related to exciting new results that just appeared, or more generally related to certain ideas.
- The Machine knows that I already know X and Y. Given that, it should be able to tell me what I should study and in what order to learn $Z$.
- "I forgot which papers I should cite for this result. I don't want to piss off people. Please remind me, Siri."
- Toss out vague idea. Machine makes concrete suggestions based on prior results from the ten million papers it has absorbed.
- Machine tosses out its own ideas on something it feels is interesting pursuing.
- Machine becomes more knowledgeable and inspiring than any human physicist, and has infinite patience.