# The conformal bootstrap

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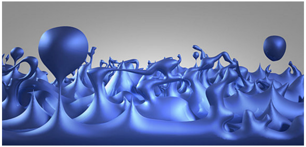
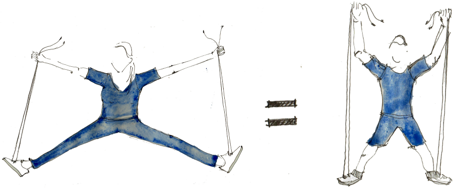
Princeton University

Seattle, July 23, 2022



# The bootstrap philosophy

**My task:** Talk about bootstrap, with emphasis on bootstrapping string theory.



- **Bootstrap** = the use of symmetry and other principles (e.g. unitarity/positivity, analyticity, crossing symmetry) to constrain (or even determine) some physical quantity
- Has been applied to:
  - **Conformal Field Theories (CFTs)** (most well developed)
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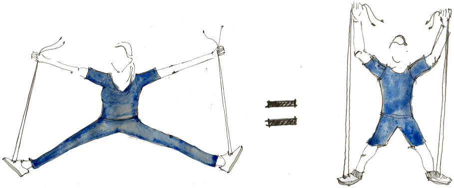

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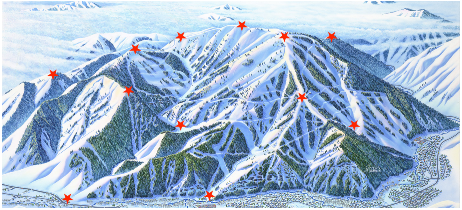
# Conformal Field Theory

- **This talk**: Focus on bootstrapping CFT.
- CFTs are QFTs with no intrinsic length/energy scale for which any angle-preserving transformation of spacetime points is a symmetry.
- May not be directly relevant for particle physics b/c CFTs have only massless excitations $E \propto |\vec{p}|$.
- **BUT:** CFTs are landmarks in the space of QFTs. They are endpoints of Renormalization Group (RG) flow, with RG flows connecting them



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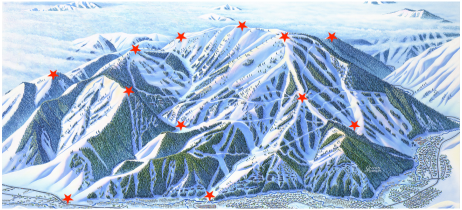

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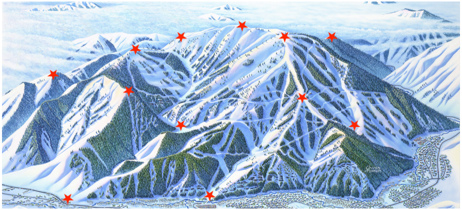

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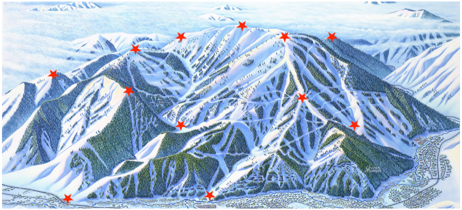

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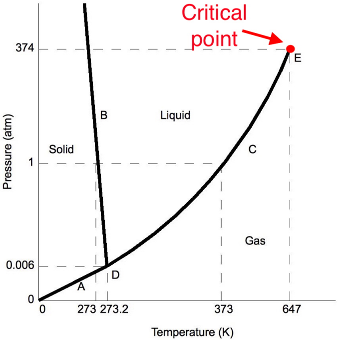
CFTs also relevant for:

- **statistical physics**: Euclidean CFTs describe 2nd order thermal phase transitions (e.g. water/vapor critical pt $T_c = 647\,\text{K}$ and $P_c = 374\,\text{atm.}$)

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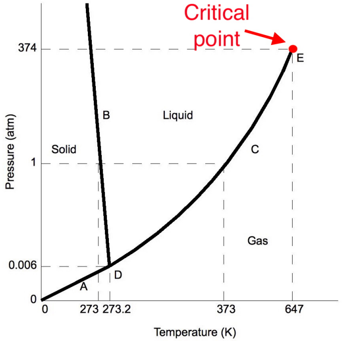


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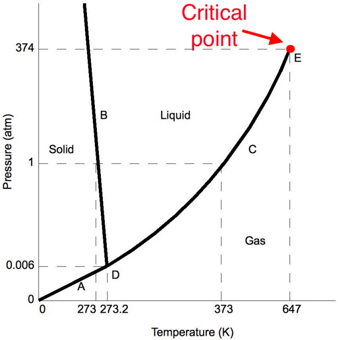


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# CFT structure

- CFTs have **local operators** $\phi_i(\vec{x})$ and **correlation functions**
- Conformal symmetry $\Longrightarrow$

$$\langle \phi_i(\vec{x}) \phi_j(\vec{y}) \rangle = \frac{\delta_{ij}}{|\vec{x}-\vec{y}|^{2\Delta_i}}$$

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  where $\Delta_{ijk} \equiv \Delta_i + \Delta_j - \Delta_k$.
  Higher pt correls can be computed from these.
- In the context of phase transitions, the scaling dimensions $\Delta_i$ are related to "critical exponents".
- For example,

$$\rho_\ell - \rho_v \propto (T_c - T)^\beta \,, \qquad \beta = \frac{\Delta_\sigma}{3 - \Delta_\epsilon}$$

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- **CFT data:** list of observables $\phi_i$ w/ their properties: $\Delta_i$ (the scaling dimensions), spin, other symmetry charges; and 3-pt function coeffs $f_{ijk}$.
- **Conformal Bootstrap** = an approach that relies on **general principles**. (No Lagrangian / action / partition function needed.)
- Idea: the computation of 4-pt functions from the CFT data imposes restrictions on the CFT data [Ferrara, Gatto, Grillo '73; Polyakov '74] .

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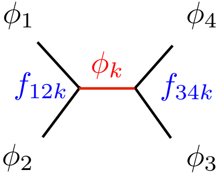
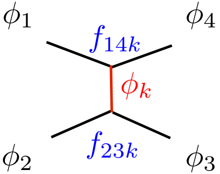
# Conformal bootstrap

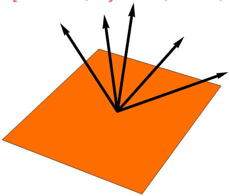
- One can compute a 4-pt function $\langle\phi_1(\vec{x}_1)\phi_2(\vec{x}_2)\phi_3(\vec{x}_3)\phi_4(\vec{x}_4)\rangle$ in two different ways, and they must agree:

$\langle\phi_1\phi_2\phi_3\phi_4\rangle = \sum_k$ 

$= \sum_k$ 

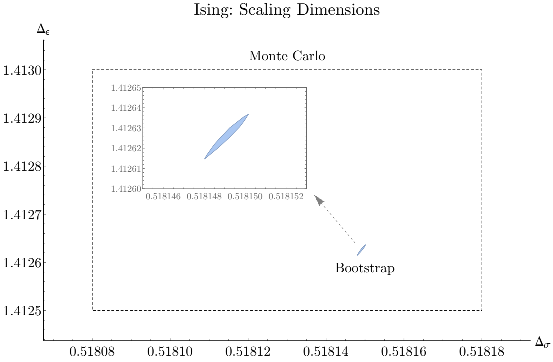

- In general, unknown set of $\phi_k$ and unknown $f_{ijk}$.

- Looking for situations that make this impossible can be rephrased as a semi-definite programming problem (numerical optimization) $\Longrightarrow$ exclude regions in CFT data space [Rattazzi, Rychkov, Tonni, Vichi, El-Showk, Kos, Paulos, Poland, Simmons-Duffin, ...] .



# Numerical results

- "Precision islands": 3d Ising, $O(N)$, Gross-Neveu-Yukawa models.
- Ising: IR fixed pt of $L = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{2} m^2 \phi^2 + \lambda \phi^4$ with $m$ tuned to $m_{\mathrm{cr}}$.

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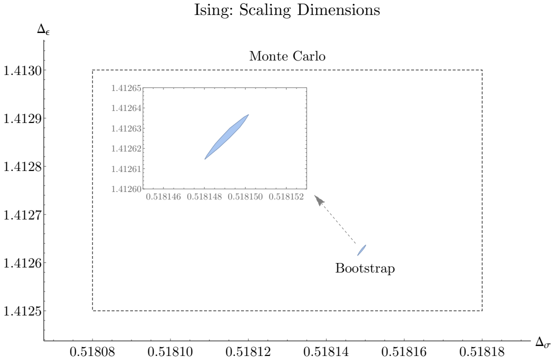


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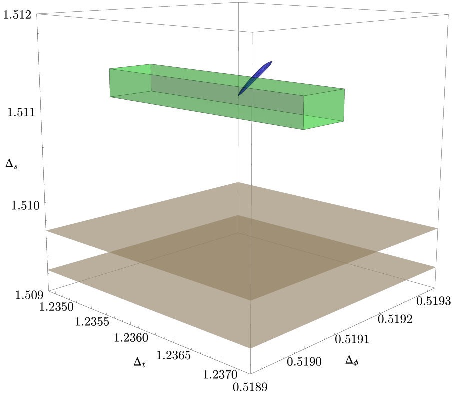
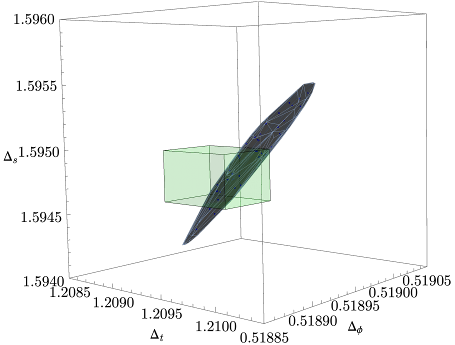
- $O(N)$ model: $L = \frac{1}{2}\sum_{i=1}^{N}\left[(\partial_\mu \phi_i)^2 + m^2\phi_i^2\right] + \lambda\left(\sum_{i=1}^{N}\phi_i^2\right)^2$. For $N = 2, 3$:




[Chester, Landry, Liu, Poland, Simmons-Duffin, Su, Vichi '19, 20']

- Next frontier: gauge theories in 3 and 4 dimensions.
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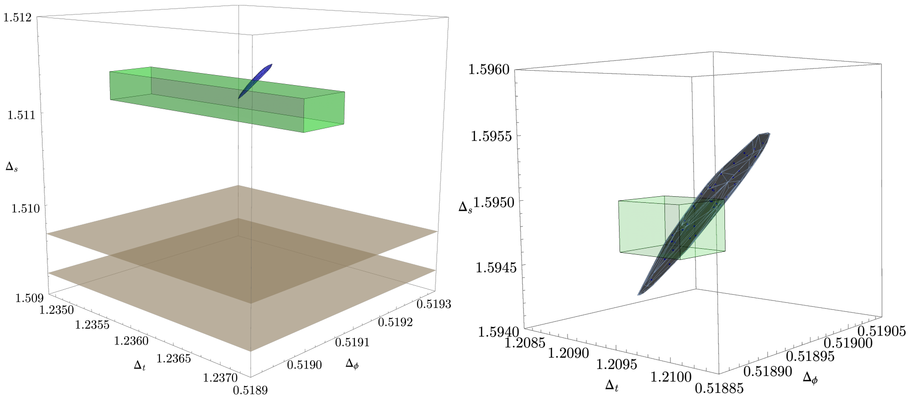


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# Bootstrapping Quantum Gravity

- Rest of the talk: what bootstrap can teach us about Quantum Gravity and string theory.

- Connection: **AdS / CFT correspondence** (gauge / gravity duality; holographic duality) [Maldacena '97; Gubser, Klebanov, Polyakov '98; Witten '98] :

  **certain CFTs that are generalizations of QCD with $N$ colors have dual descriptions in terms of gravity w/ negative cosmological constant** (as a limit of string theory or M-theory)

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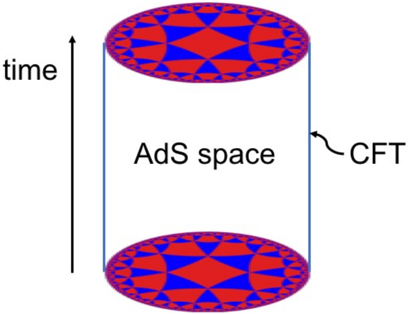
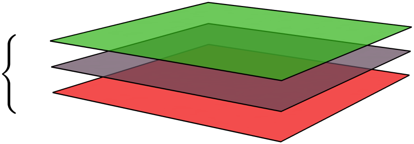
# AdS/CFT

- Precise correspondence:
  CFT quantities (e.g. correlation functions) can be computed from the bulk.




- $L/\ell_p \propto N^{\#}$ where $L$ is the curvature radius of AdS, and $\ell_p$ is the Planck length.
- (Semi-classical) gravity is a good approximation when the number of colors $N$ is large ($\Longrightarrow L/\ell_p$ is large, i.e. the curvature of spacetime is small)

# Examples

$N$ 

Examples of CFTs with AdS duals (both with maximal SUSY):

- $\mathcal{N} = 4$ supersymmetric Yang-Mills theory in $3 + 1$ dimensions.
  - $L/\ell_p \propto N^{1/4}$.
  - Dual to $AdS_5 \times S^5$.
  - Describes physics of $N$ membranes in 10-dimensional string theory.
- ABJM theory in $2 + 1$ dimensions [Aharony, Bergman, Jafferis, Maldacena '09] .
  - $L/\ell_p \propto N^{1/6}$.
  - Dual to $AdS_4 \times S^7$.
  - Describes physics of $N$ membranes in 11-dimensional M-theory.

# Study Quantum Gravity through CFT

- What can one learn about string theory / Quantum Gravity by studying these CFTs?

- Example: **graviton scattering** [Polchinski, Giddings, Penedones, Fitzpatrick, Kaplan, Goncalves, . . . ]

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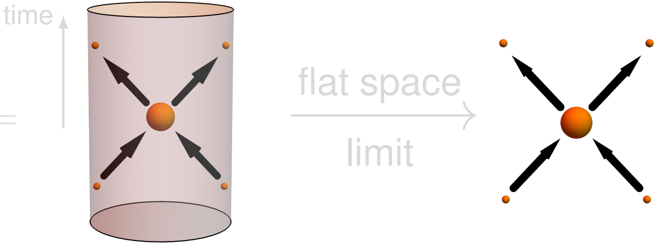


(4 graviton scattering = 4-point function of stress-energy tensors)

(collider analogy: learn about new particles by scattering particles we can create)

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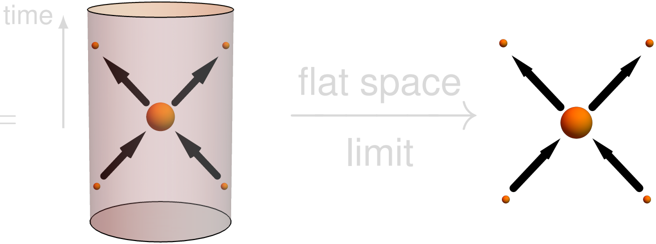


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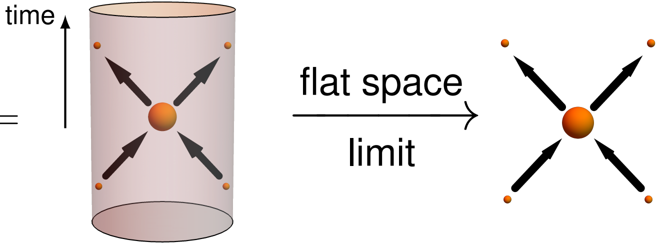


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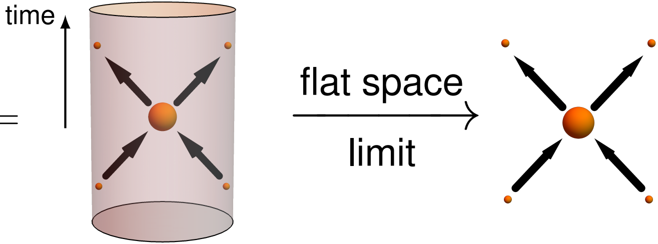


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# Study Quantum Gravity through CFT

Of all CFTs w/ AdS duals, the most constrained are those with **supersymmetry** (such as $\mathcal{N} = 4$ SYM or ABJM theory), for which one can compute "protected" quantities.

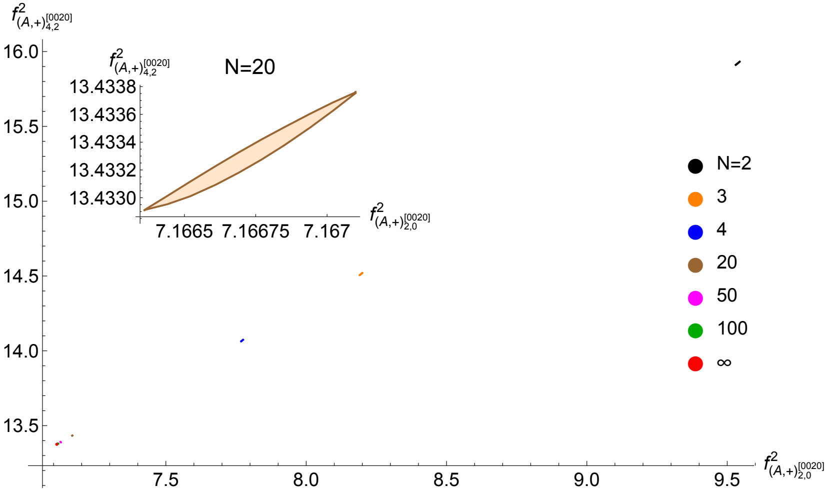
- Example: integrals of correlators of certain operators.

Ongoing efforts → numerical, at small *N*

Ongoing efforts → analytical, at large *N*

# Numerical study in ABJM theory (in 2 + 1 dimensions)

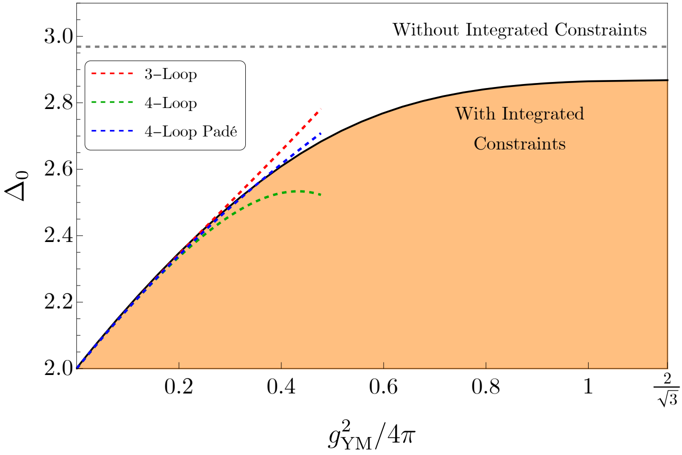
Numerical bootstrap **islands** for ABJM theory [Chester, Lee, SSP, Yacoby '14; Agmon, Chester, SSP '19] (uses SUSY [Dedushenko, Fan, SSP, Yacoby '16, '17, '18]).



# Numerical study in $\mathcal{N} = 4$ SYM (in $3 + 1$ dimensions)

Numerical bootstrap **bounds** on lowest unprotected op in $SU(2)$ $\mathcal{N} = 4$ SYM

[Chester, Dempsey, SSP '19]




Bounds can be improved by including more SUSY info, mixed correlators, etc.

# Analytic bootstrap: a 4d example

- In $\mathcal{N} = 4$ SYM, schematically at **fixed** $g_{\mathbf{YM}}$

$$\langle TTTT \rangle = 1 + N^{-2} + N^{-\frac{7}{2}} + N^{-4} + N^{-\frac{9}{2}} + \cdots$$

  and each coefficient can be determined from Witten diagrams.

- Analytic properties of Witten diagrams + symmetry + exact results from SUSY completely determine $\langle TTTT \rangle$ at the first few orders in $1/N$.

- Flat space limit of $\langle TTTT \rangle \Longrightarrow$ the first few corrections to the Einstein-Hilbert action (as seen by graviton scattering). Schematically:

$$S_{10\text{d}} = \int \sqrt{-g} \left[ R + \text{Riemann}^4 + D^4 \text{Riemann}^4 + \cdots \right]$$

  [Chester, SSP, Yin '18; Binder, Chester, SSP, Wang '19; Binder, Chester, SSP '19; Chester, Green, SSP, Wang, Wen '19, '20] (See also [Alday, Bissi, Perlmutter, Heslop, Paul, . . . ] ).

- Can derive the $\text{Riemann}^4$, $D^4\text{Riemann}^4$ terms in 10-dimensional string theory (and also in 11-dimensional M-theory from ABJM theory) **from CFT bootstrap + SUSY**!

# Comments

- Bootstrap is **crucial**, b/c the standard technique (Witten diagrams in AdS) cannot be used due to the fact that the interaction vertices are not fully known.
- In $\mathcal{N} = 4$ SYM, $\langle TTTT \rangle$ is a fn of two params: $N$ and $g_{\rm YM}$.
  - $g_{\rm YM}^2 \leftrightarrow g_s$ (string coupling)
  - $1/N \to$ (small momentum expansion of scattering amplitudes)
- In flat space, graviton S-matrix is known:
  - At leading order in $g_{\rm YM}$ exactly in momentum (Virasoro-Shapiro)
  - At low orders in momentum ($R^4$, $D^4 R^4$, $D^6 R^4$) exactly in $g_{\rm YM}$.
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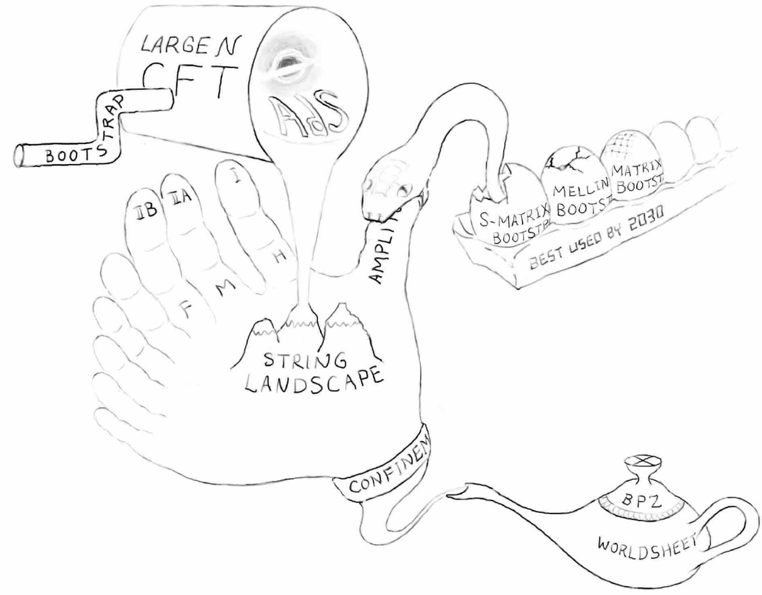
# Conclusion and other directions

- CFT gives a universal language that applies to a variety of systems that exhibit 2nd order phase transitions and even to **Quantum Gravity**.

**Other ways to bootstrap string theory:**

- Bootstrap S-matrices directly. Lots of progress recently. [Vieira, Penedones, Guerrieri, Caron-Huot, Rastelli, Simmons-Duffin, Mazac, . . . ]
- Bootstrap worldsheet CFT (perhaps together with dual CFT).
- Instead of OPE decomposition, use a different expansion of the correlation function. (Mellin bootstrap?) [Gopakumar, Kaviraj, Sen, Sinha, . . . ]
- Finite temperature bootstrap [Iliesiu, Kologlu, Mahajan, Perlmutter, Simmons-Duffin, . . . ]
- Swampland questions: is it possible to rule in/out scale separated AdS vacua? String universality?
- Bootstrapping de Sitter Quantum Gravity [Arkani-Hamed, Baumann, Lee, Pimentel, Pajer, Stefanyszyn, Supel, Goodhew, Jazayeri, Sleight, Taronna, Duaso Pueyo, Joyce, Meltzer, Di Pietro, Gorbenko, Komatsu, Hogervorst, penedones, Vaziri, . . . ]




*[Illustration by Xi Yin, from [Gopakumar, Perlmutter, Pufu, Yin '22] ]*