Title: Towards 3-Point Correlation Functions of Heavy Operators

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Abstract: In this talk I will report on the computation at strong coupling of the AdS contribution to the 3-point correlation function of operators corresponding to classical strings which rotate in the S5. This contribution is universal for all operators which have only SO(6) charges.

Towards 3-Point Correlation Functions of Heavy Operators

Romuald A. Janik

Jagiellonian University
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IGST 2011
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RJ, A. Wereszczyński: to appear
Many thanks to Amit & Pedro

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1. **Introduction**
2. **2-point correlation functions**
   - Brief review
3. **3-point correlation functions**
   - General features
   - Pohlmeyer reduction
   - Regularized 'Pohlmeyer' area
   - Overlaps between solutions of the linear system
   - Worldsheet cut-off versus target space cut-off
4. **Final answer**
5. **Summary & outlook**

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- Find the spectrum of conformal weights
  $\equiv$ eigenvalues of the dilatation operator
  $\equiv$ (anomalous) dimensions of operators

$$\langle O(0)O(x)\rangle = \frac{1}{|x|^{2\Delta}}$$

- Find the OPE coefficients C_{ijk} defined through

$$\langle O_i(x_1)O_j(x_2)O_k(x_3)\rangle = \frac{C_{ijk}}{|x_1-x_2|^{\Delta_i+\Delta_j-\Delta_k}|x_1-x_3|^{\Delta_i+\Delta_k-\Delta_j}|x_2-x_3|^{\Delta_j+\Delta_k-\Delta_i}}$$

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- BPS operators correspond to supergravity modes
- Their anomalous dimensions are protected as well as OPE coefficients
- These states are (in this context) commonly called **light states**

- Operators which have nontrivial anomalous dimensions correspond to massive string states
- The lightest of these, corresponding to 'short strings' (e.g. the Konishi operator) can be called by analogy **medium states**

- A subclass of operators with large R-charges/spins correspond, at strong coupling, to classical string states
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We will be interested in a subset of the **heavy** states whose whole dynamics is concentrated in the S^5 part of $AdS_5 \times S^5$

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- At weak coupling (for *unprotected* operators) a lot is known at tree-level and at 1-loop, as well as Frolov-Tseytlin limit — see talk by Gromov
- At strong coupling, the case of 3-point correlation functions/OPE coefficients C_{HHL} for two **heavy** and one light is well studied — Zarembo; Costa et al.
  — use the known classical solution for a two-point function of the heavy operators and integrate with the propagator of the light supergravity mode
- Recently near BMN operators were also considered — Klose, McLoughlin

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- For a three-point function, we have to construct a classical solution with the topology of a **thrice punctured sphere**

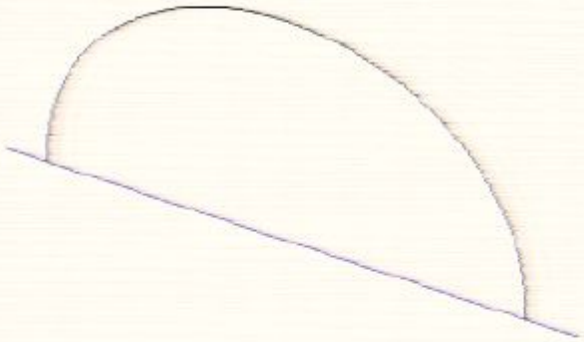
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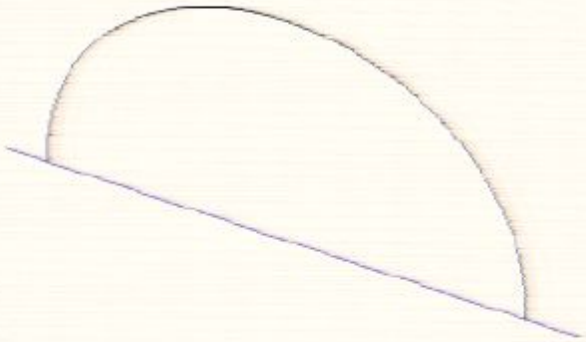
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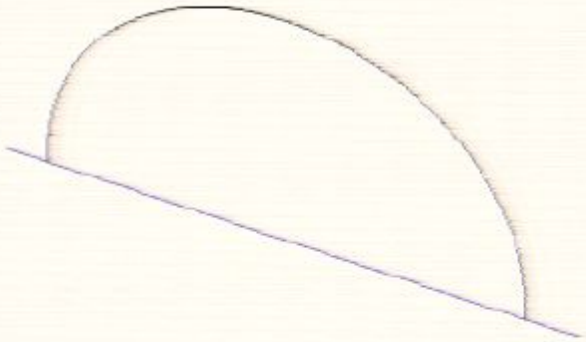
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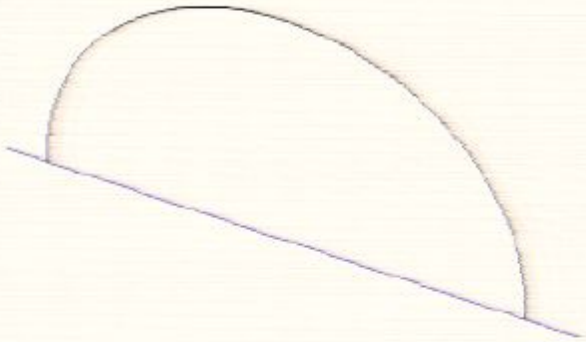
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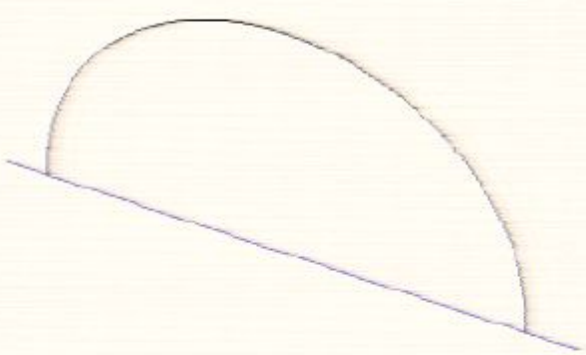
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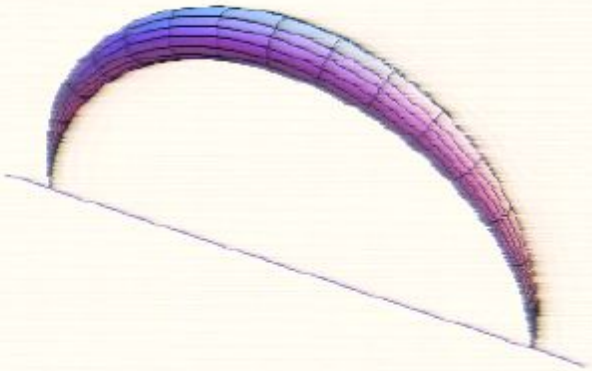


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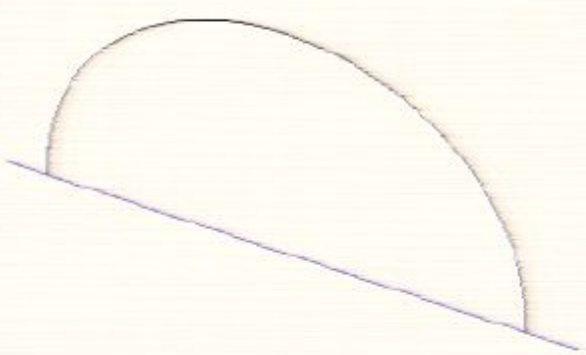


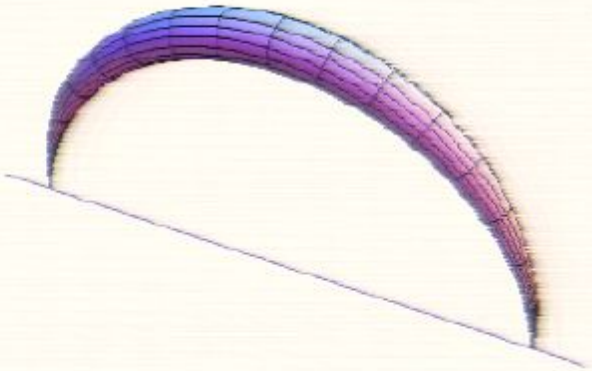


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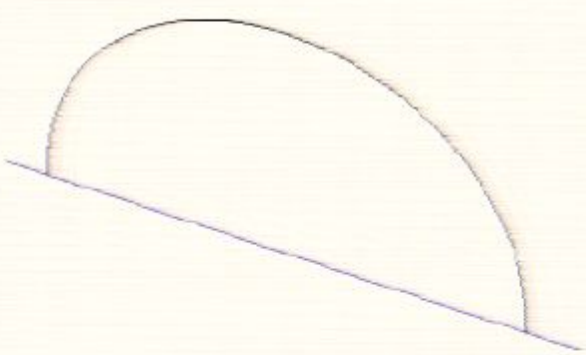


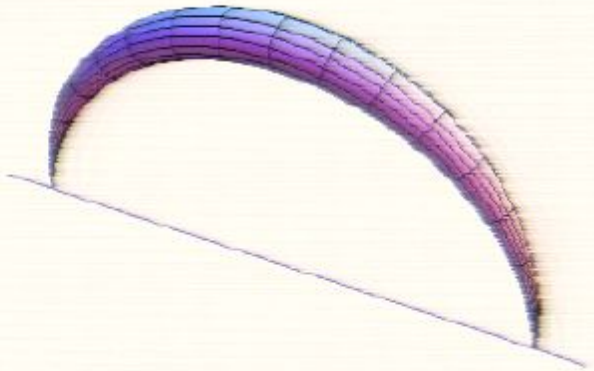


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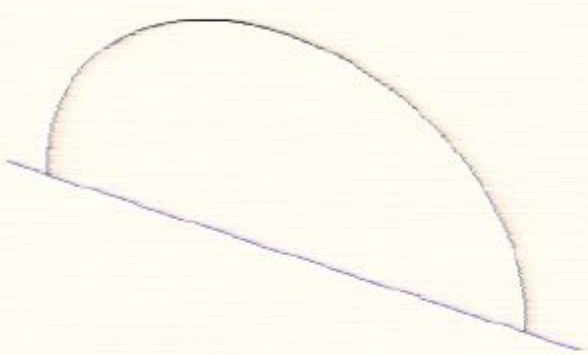


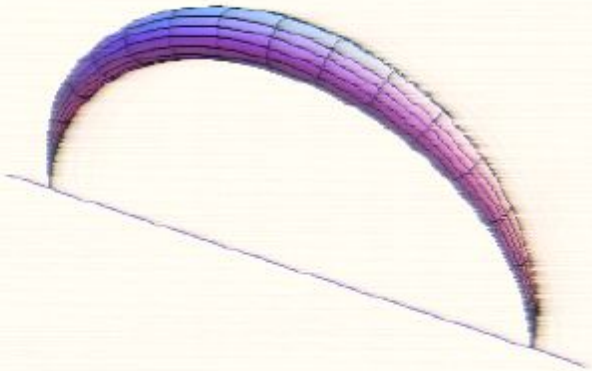


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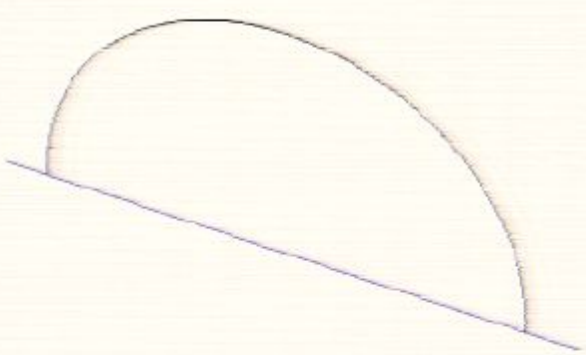


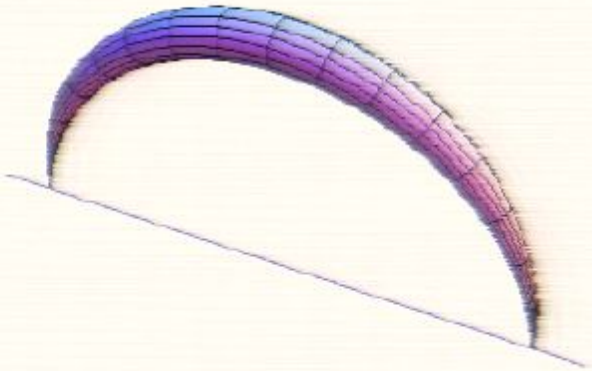


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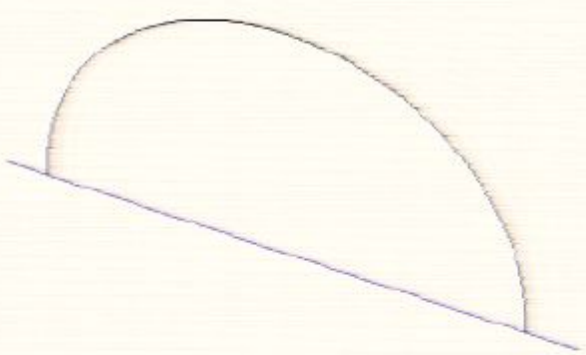


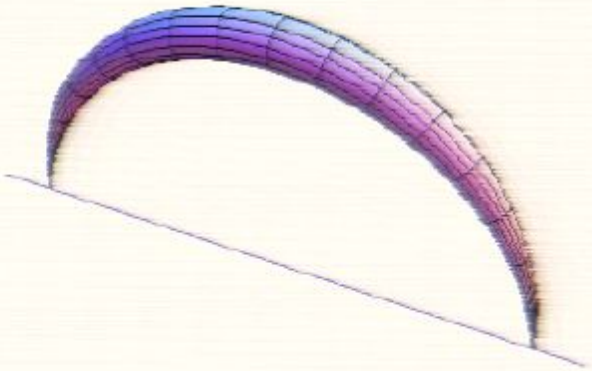


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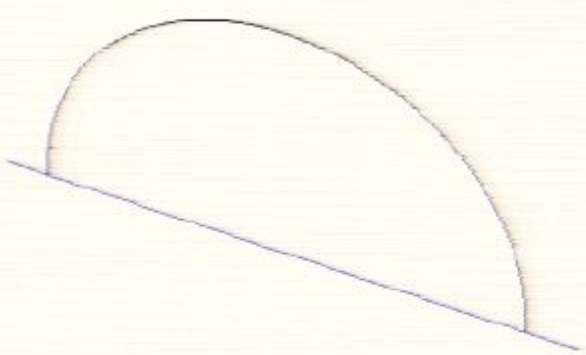


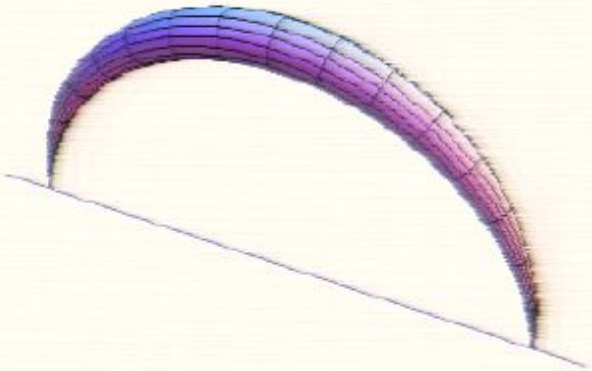


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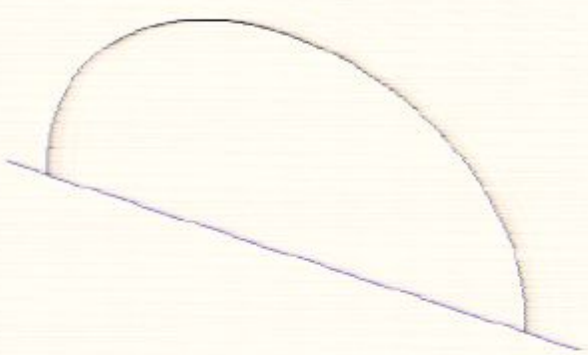


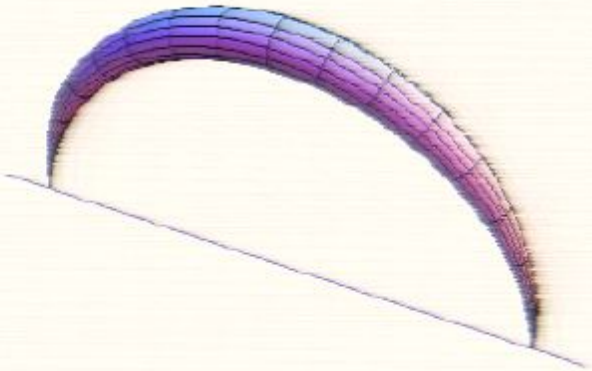


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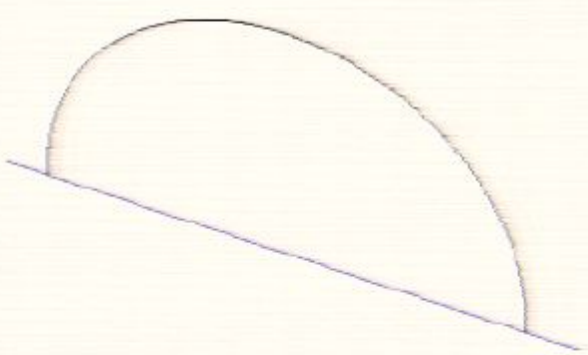


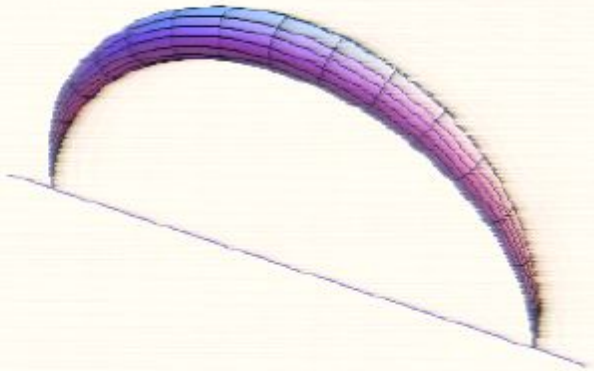


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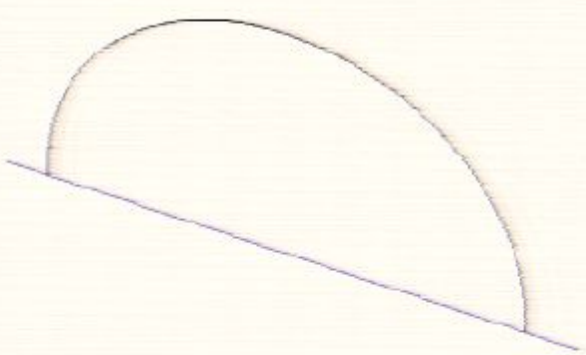


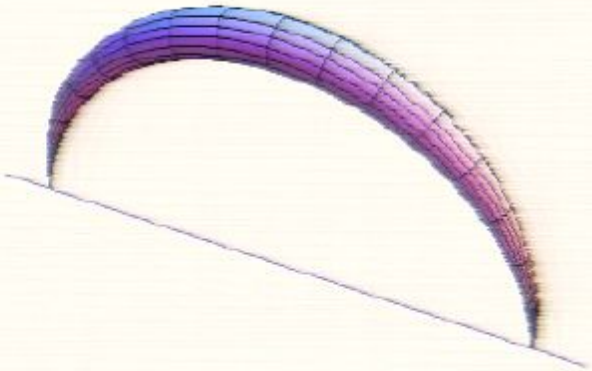


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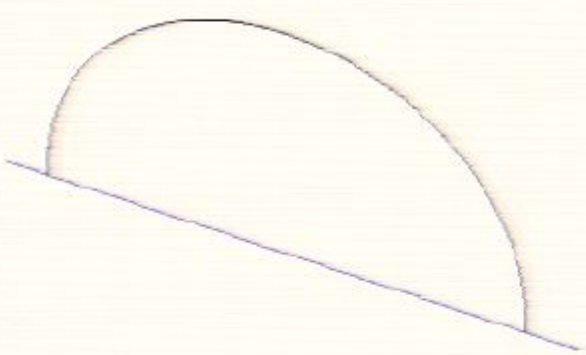


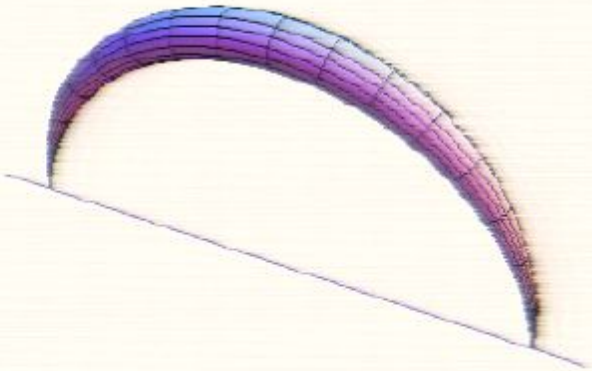


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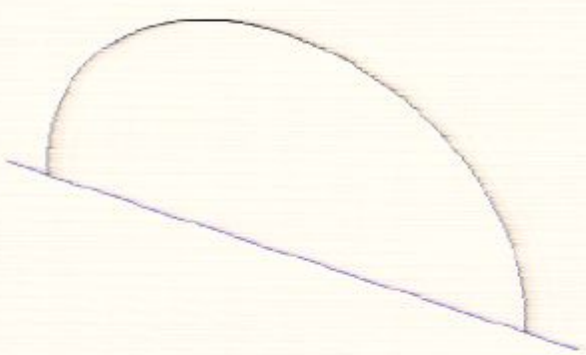


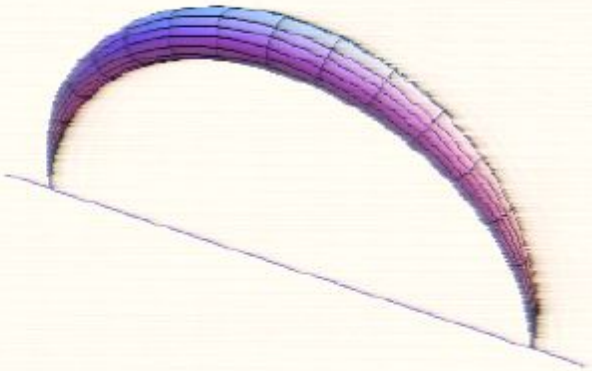


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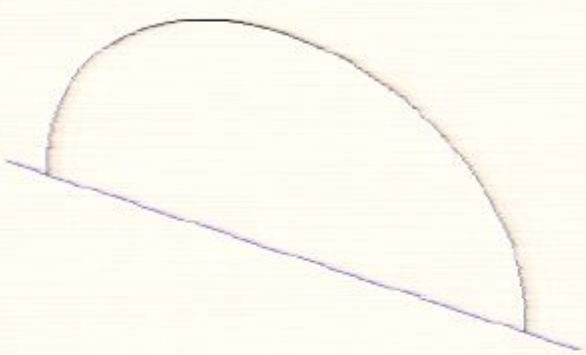


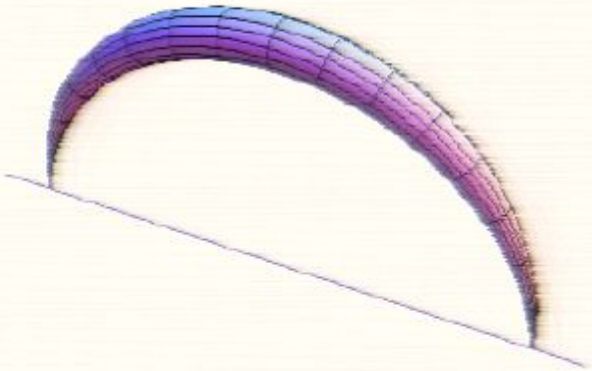


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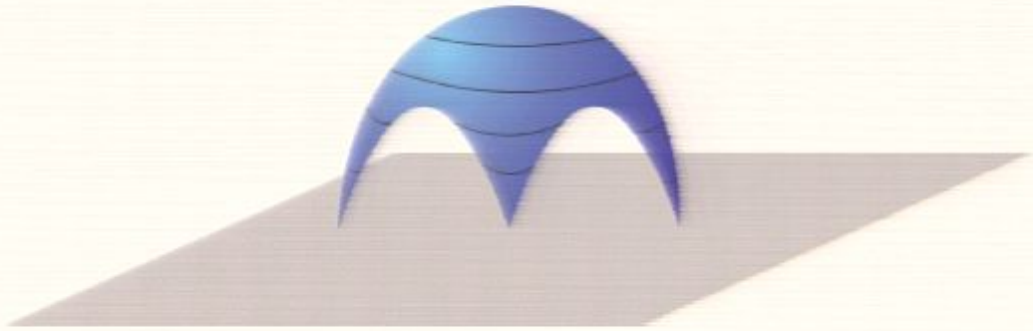
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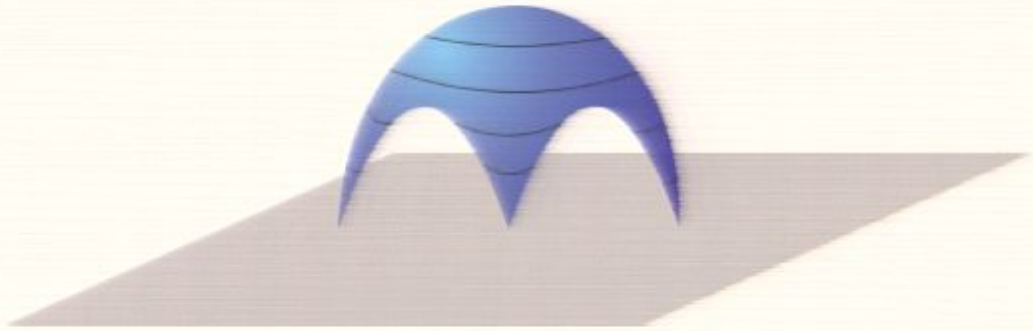


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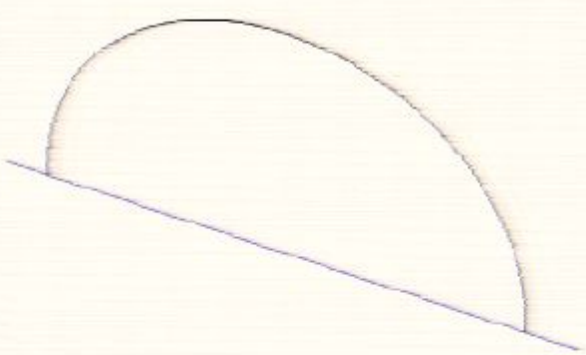


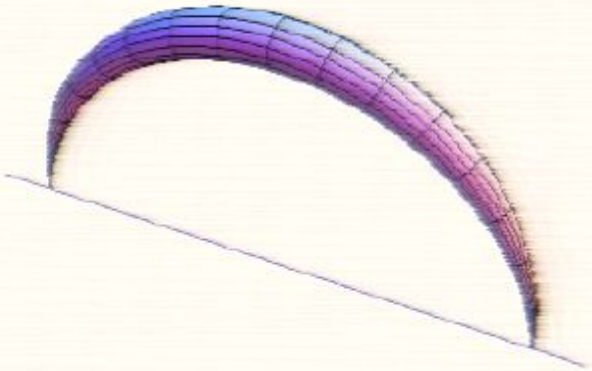
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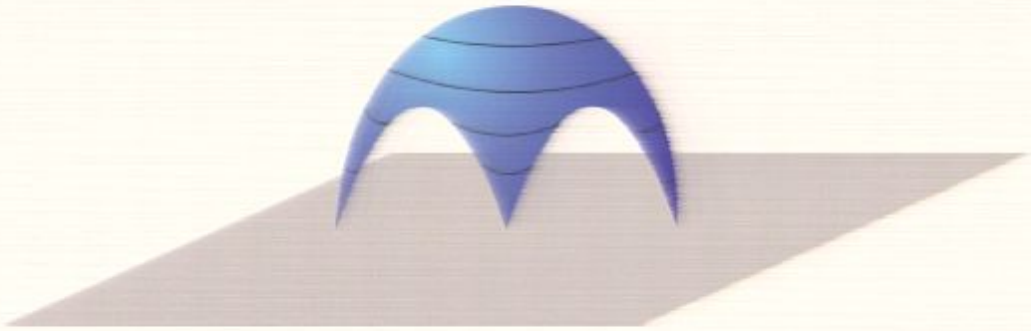
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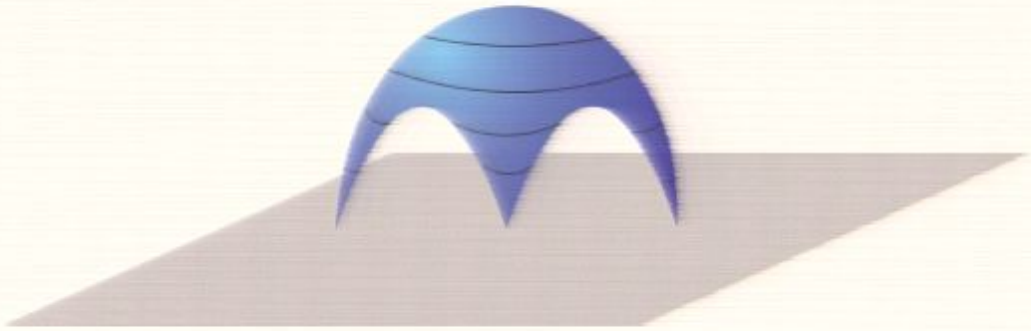


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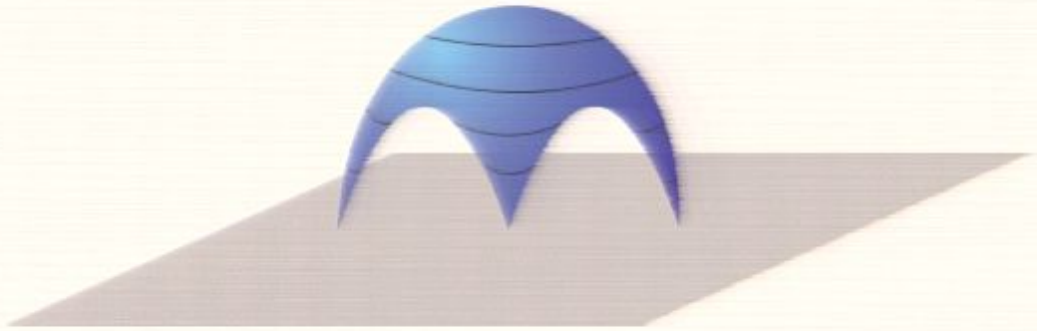


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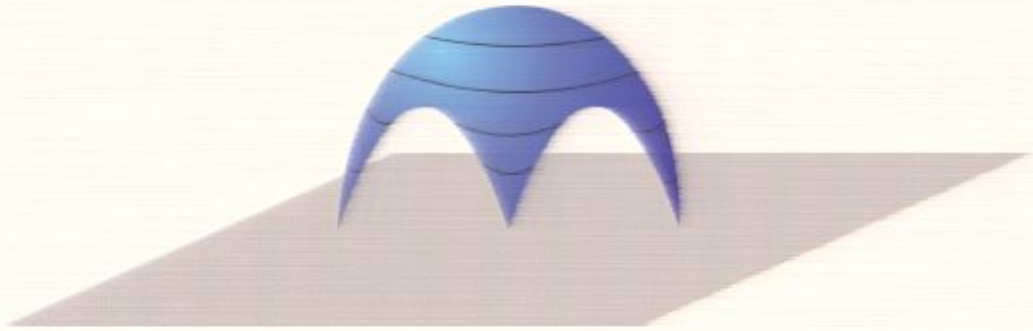


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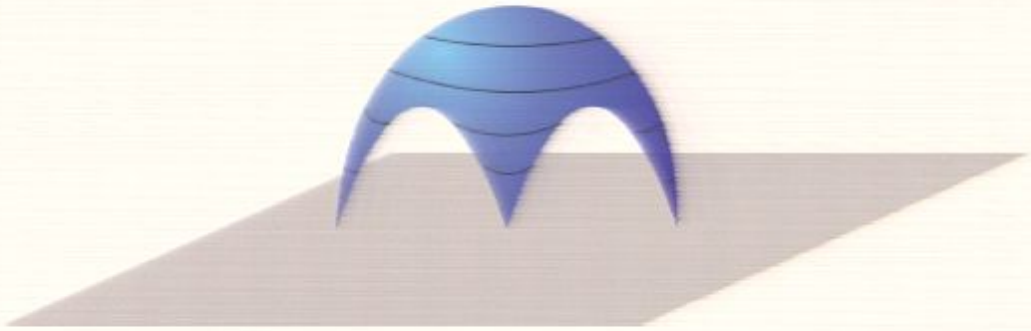


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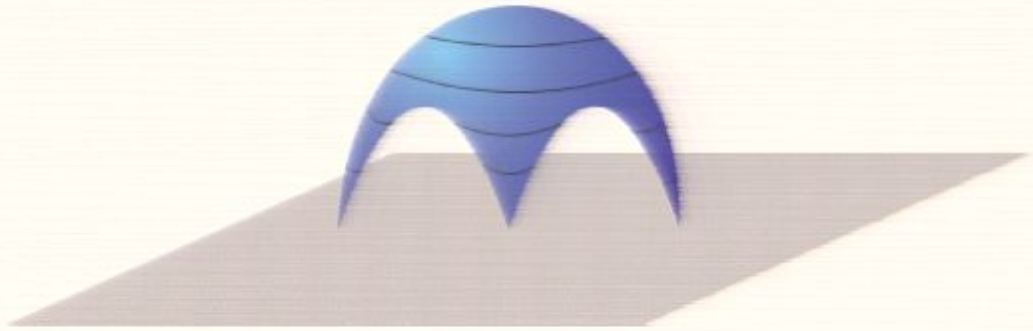


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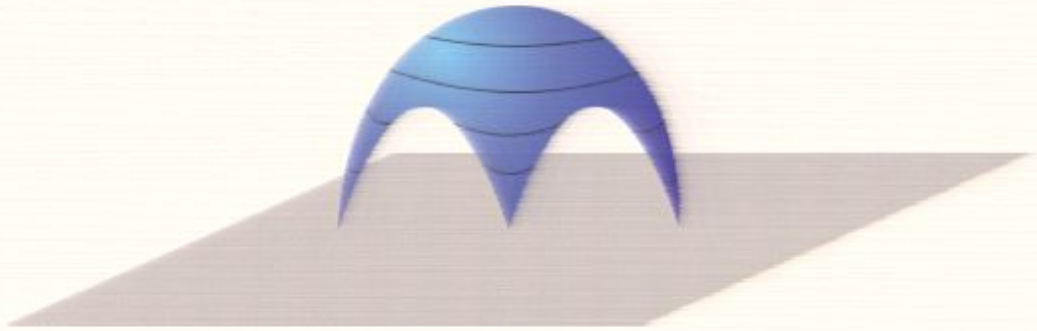
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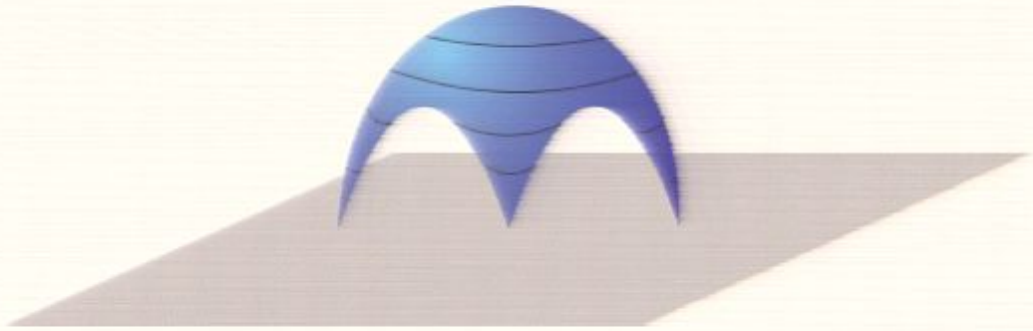


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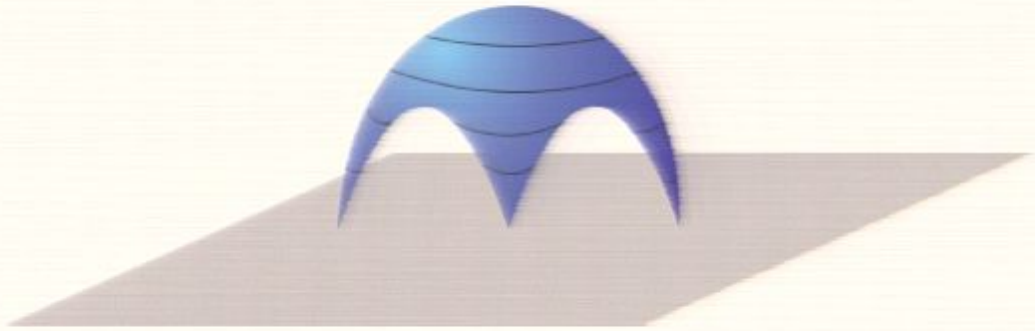


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3-point correlation functions

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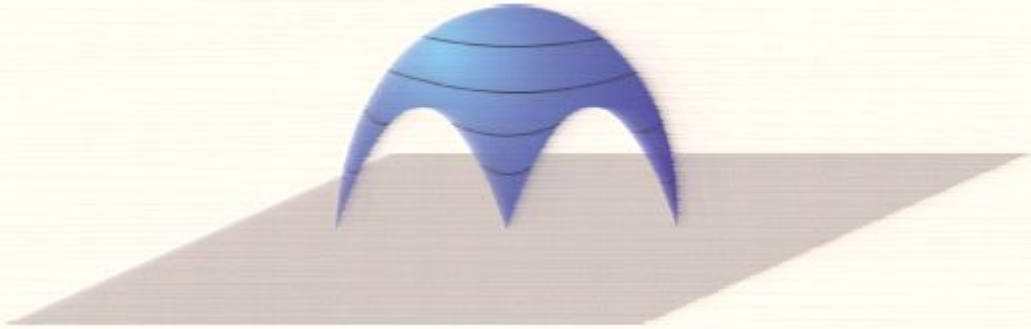
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$$T_{AdS}(w) + T_{S^5}(w) = 0$$

(w is a holomorphic coordinate on the punctured sphere)

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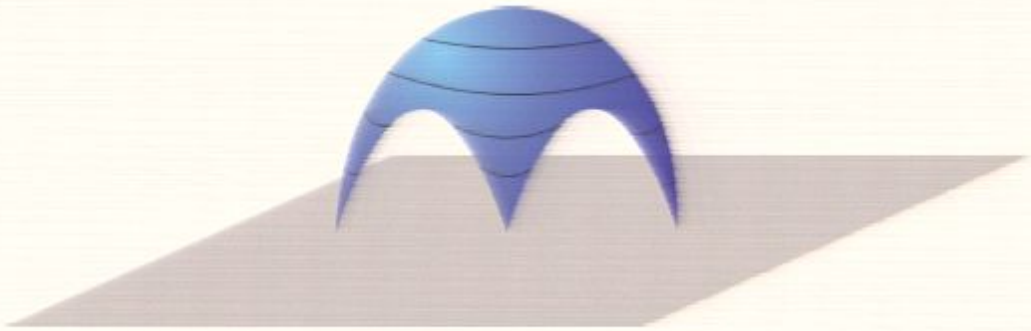
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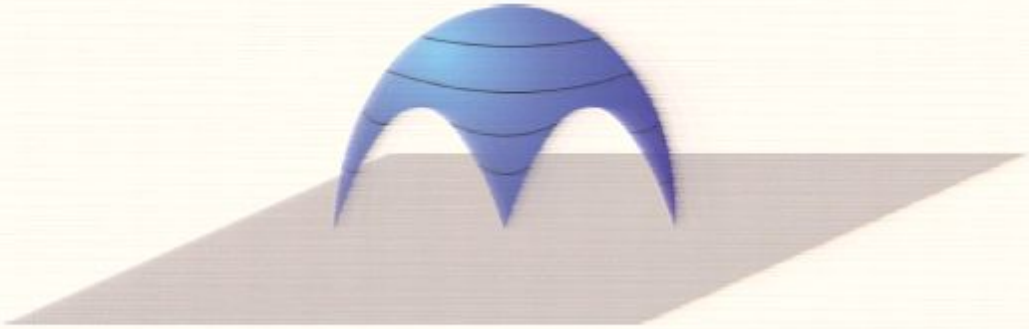
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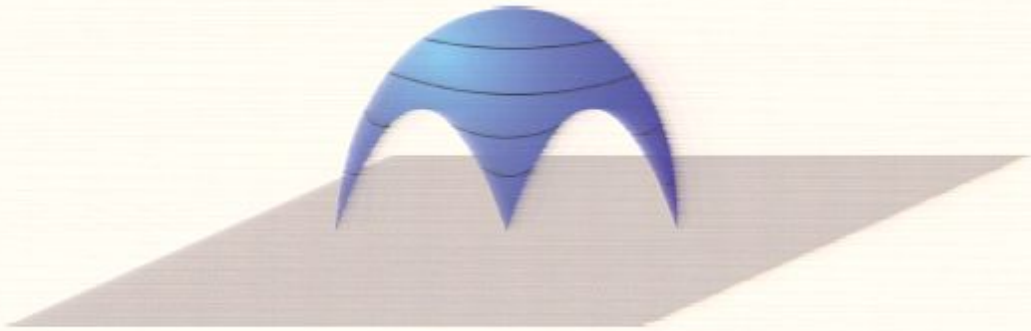
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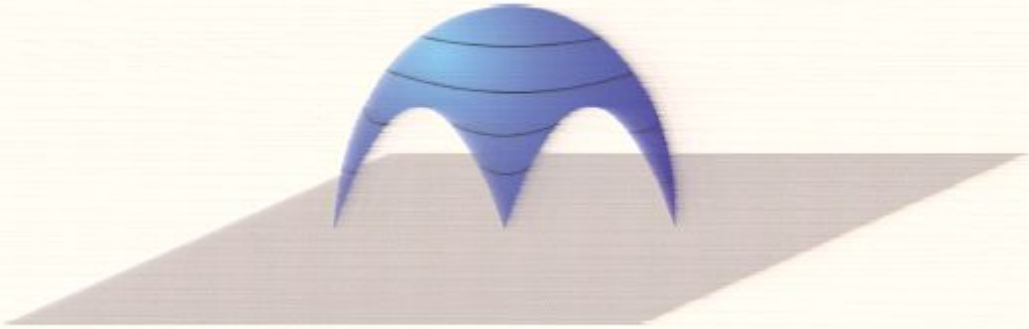
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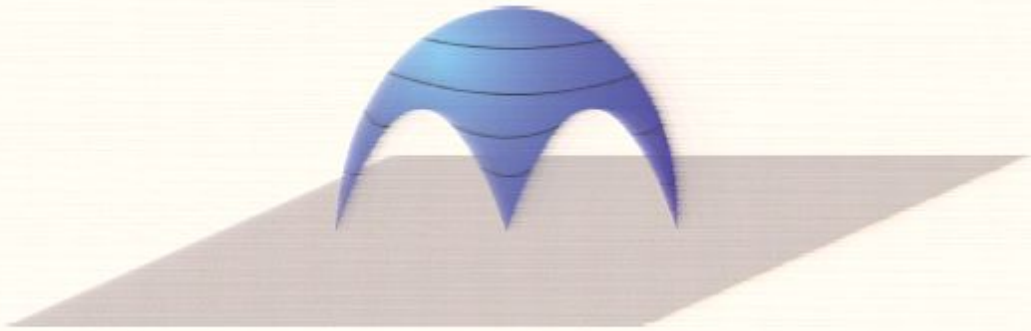
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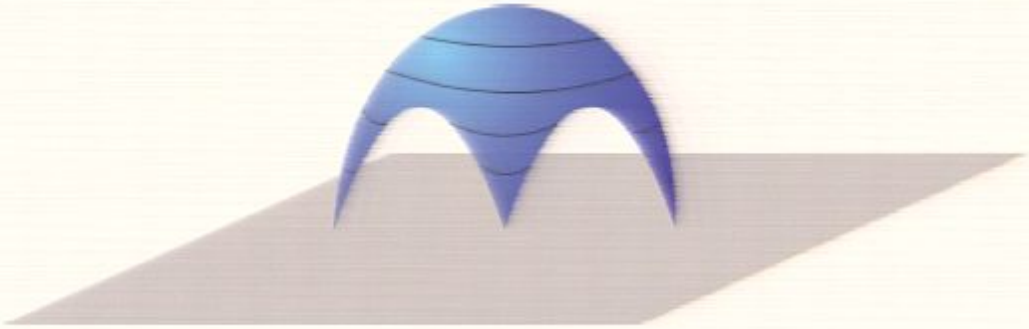
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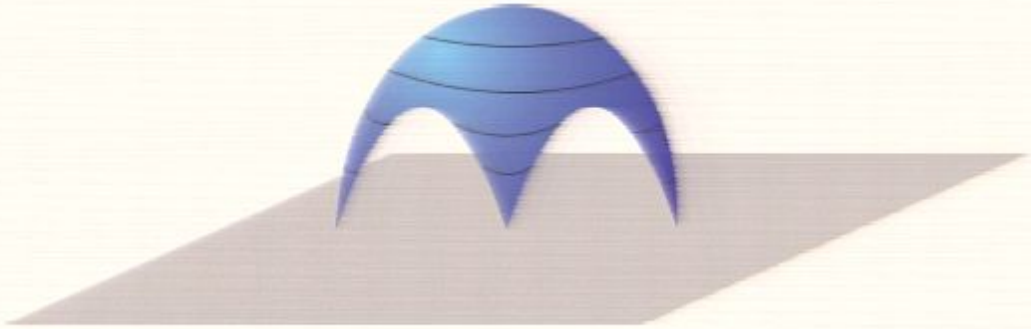
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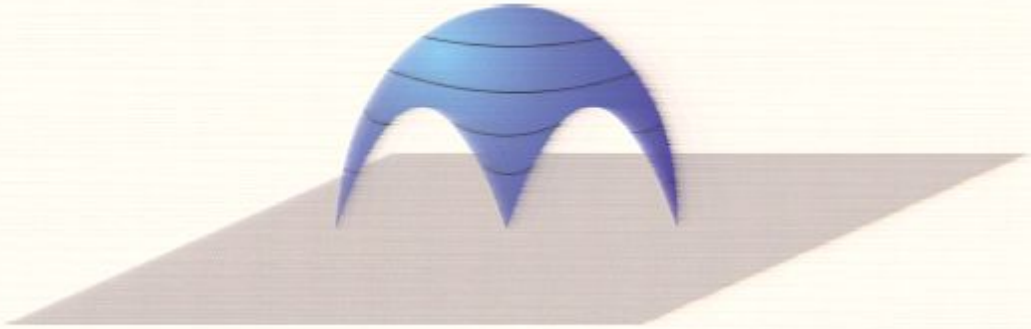
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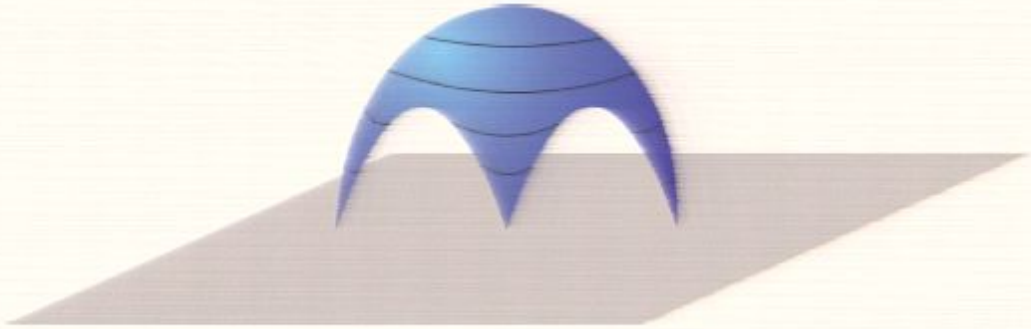
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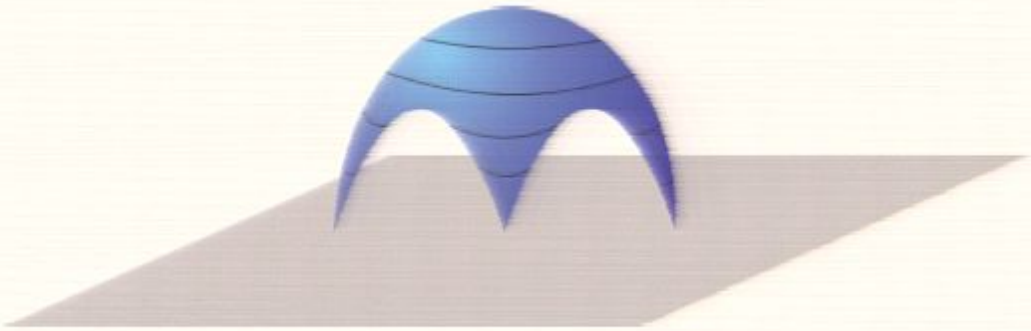
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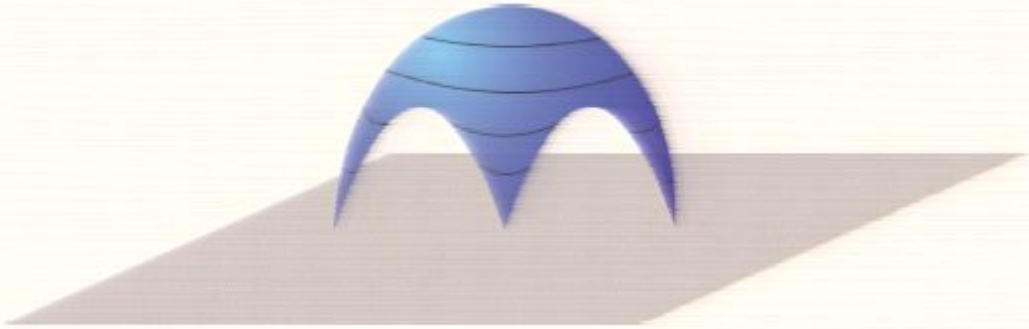
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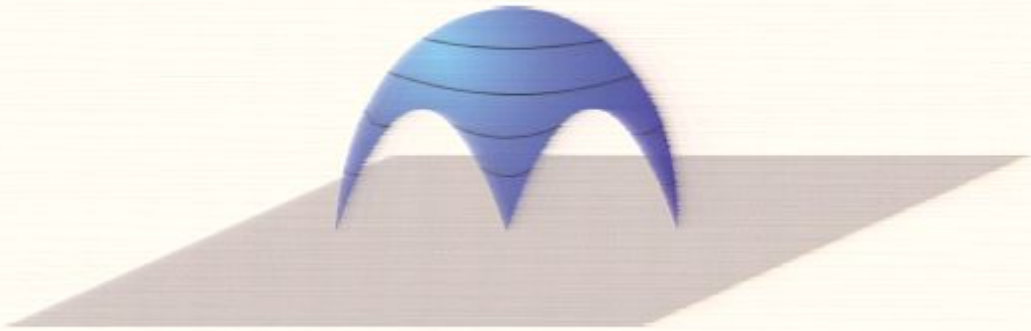
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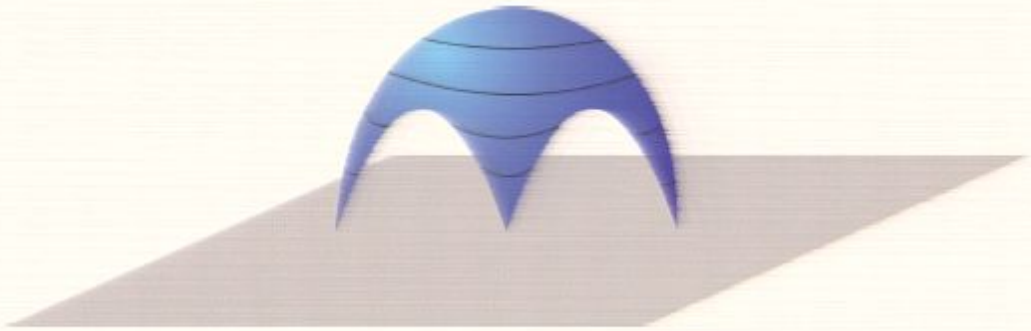
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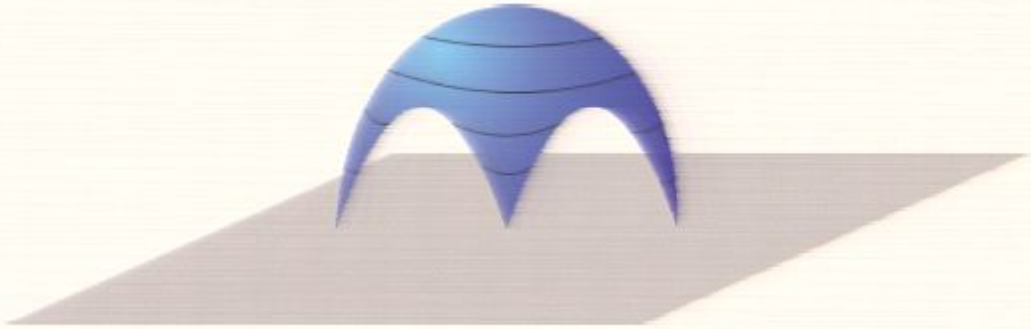
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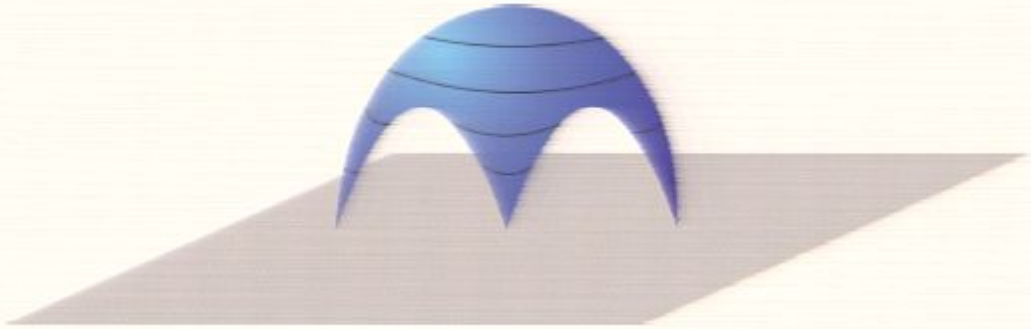
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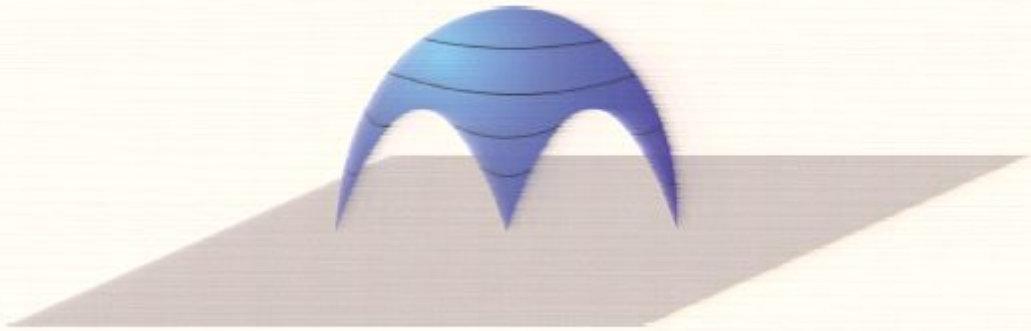
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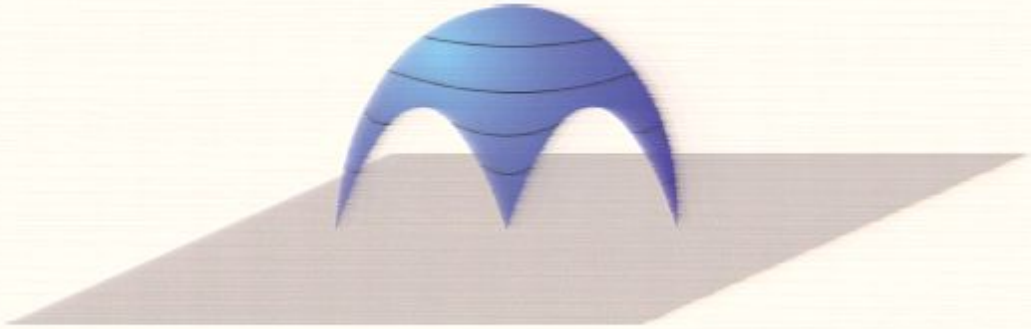
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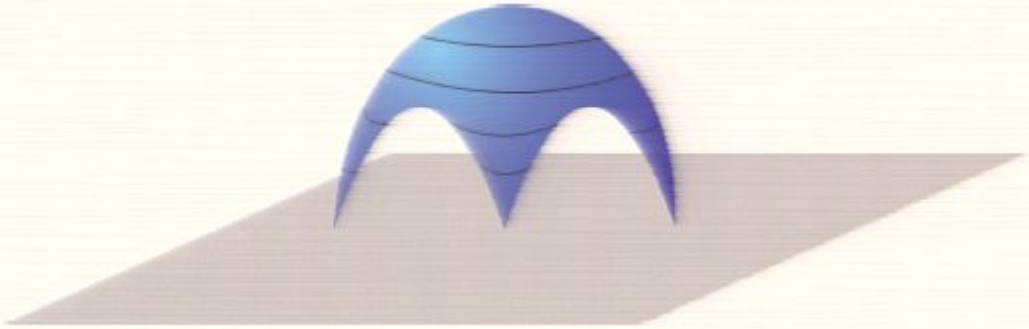
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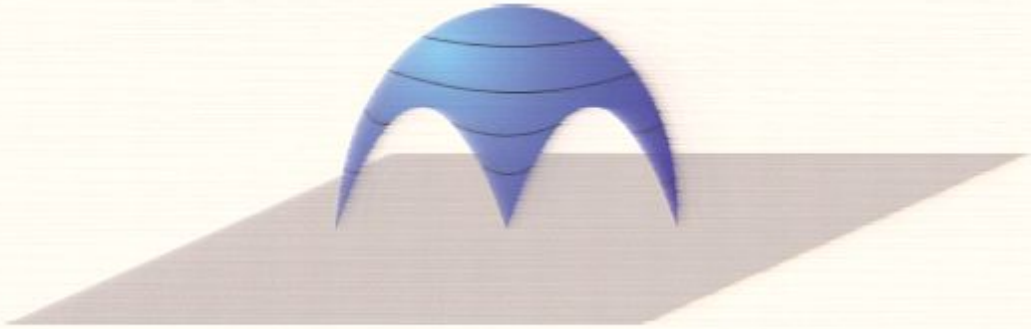
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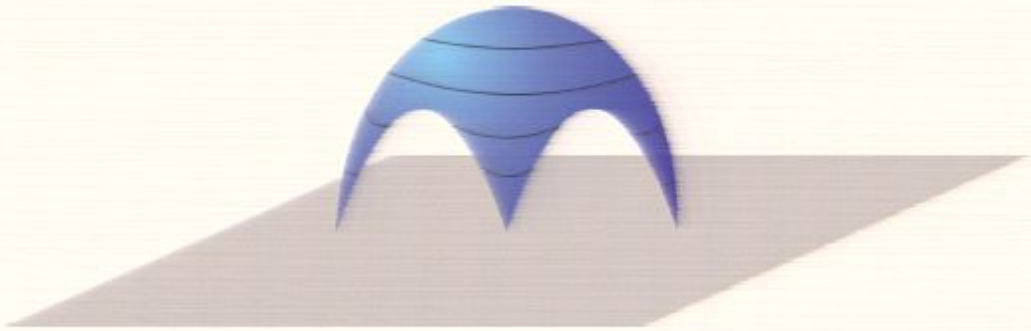
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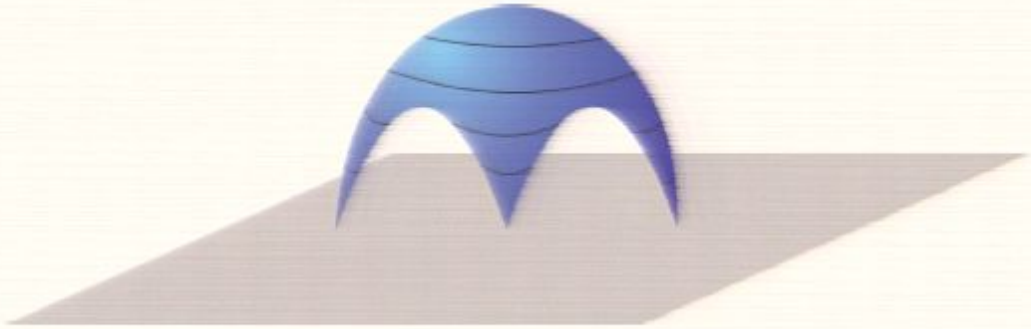
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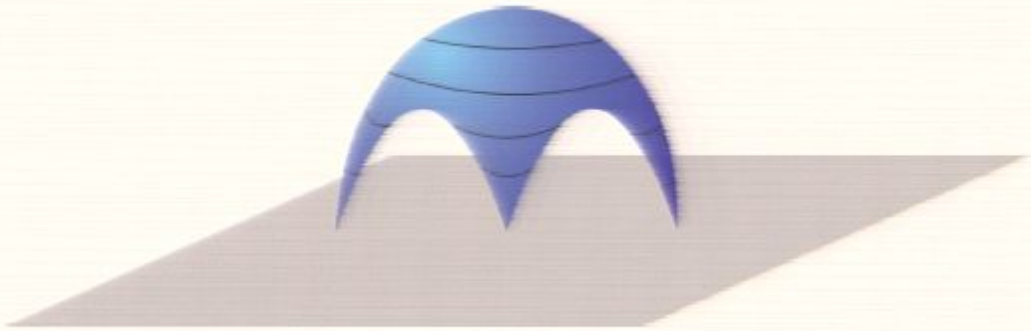
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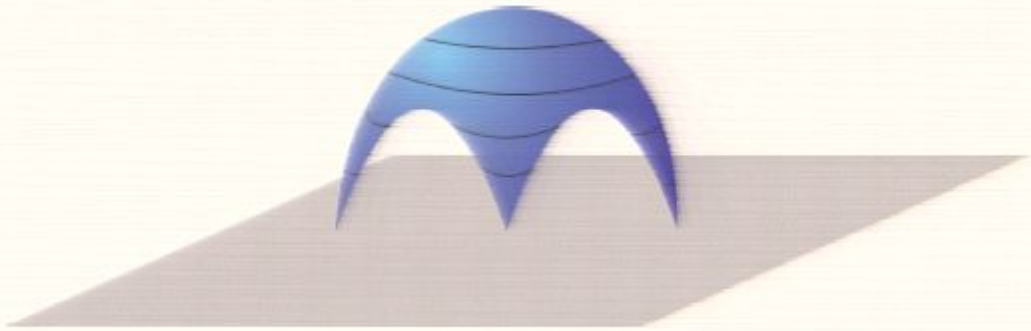
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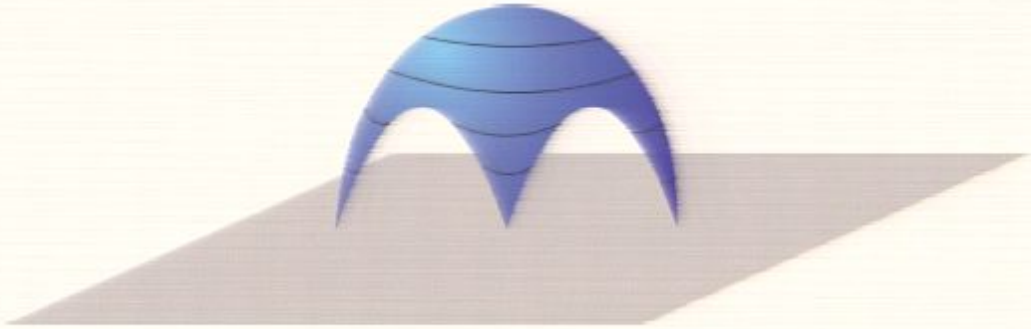
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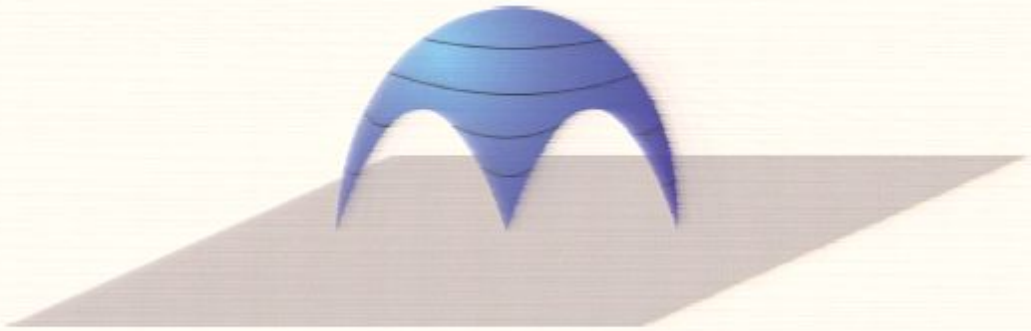
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- Involves wave functions of the appropriate states
- *A-priori* very complicated

The AdS part

- By putting the (gauge theory) operator insertions on a line, we can reduce the problem just to an AdS_2 subspace
- **Note:** this is not a minimal area problem! ($T_{AdS}(w) \neq 0$)
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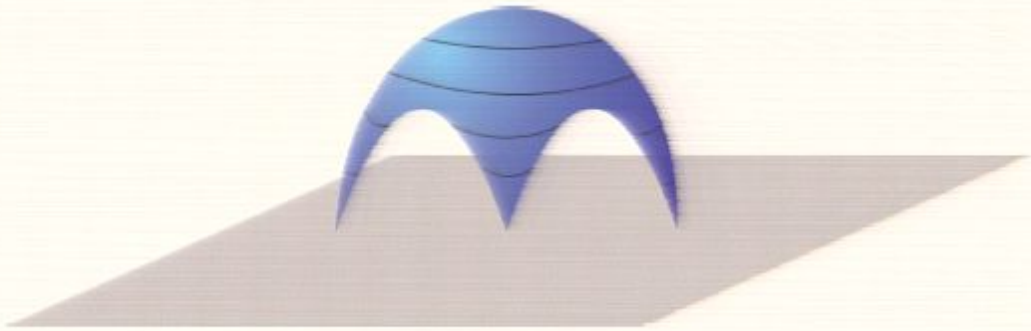
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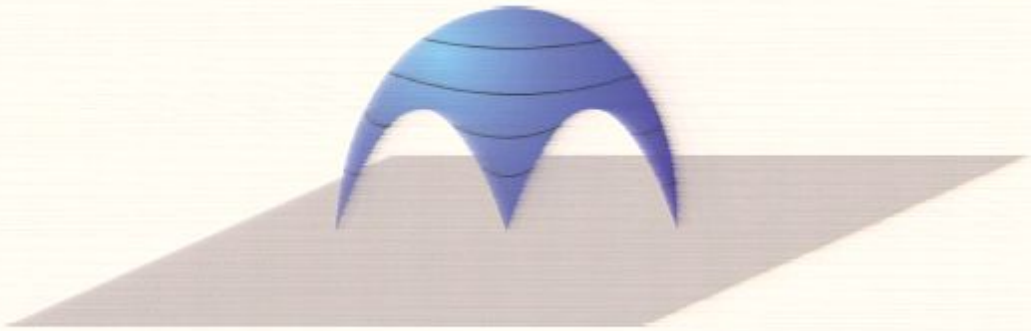
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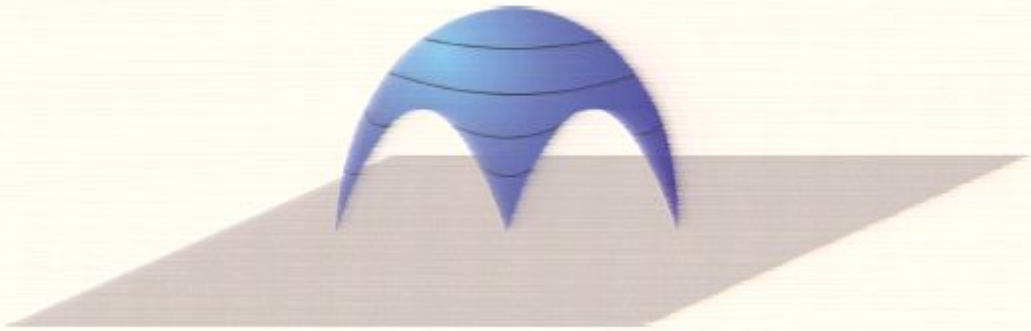
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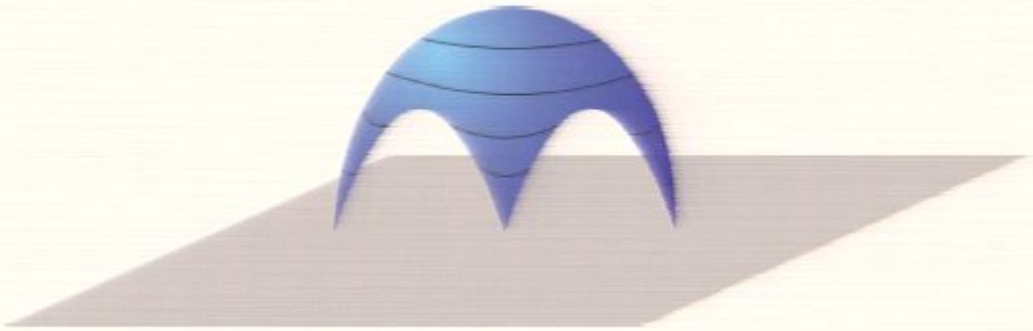
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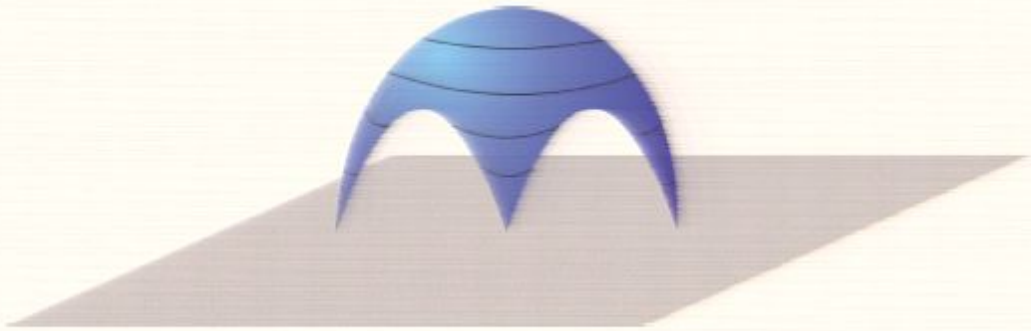
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- The generalized sinh-Gordon model is integrable
- There exists a family of flat connections

$$J = \frac{1}{\xi}\Phi_w\, dw + A + \xi\, \Phi_{\overline{w}}\, d\overline{w}$$

- Flatness is equivalent to the compatibility of the linear system

$$\partial\Psi + J_w\Psi = 0 \qquad \overline{\partial}\Psi + J_{\overline{w}}\Psi = 0$$

- Around each puncture we have two solutions (k and $\overline{k}$) with monodromies

$$e^{\pm i\Delta_k \frac{\pi}{2}\left(\xi - \frac{1}{\xi}\right)}$$

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$$e^{\pm i\Delta_k \frac{\pi}{2}\left(\xi - \frac{1}{\xi}\right)}$$

Pohlmeyer reduction

- The generalized sinh-Gordon model is integrable
- There exists a family of flat connections

$$J = \frac{1}{\xi}\Phi_w\, dw + A + \xi\,\Phi_{\overline{w}}\, d\overline{w}$$

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Area:

$$\int_{\Sigma\setminus\{\varepsilon_i\}} \frac{\partial x\bar{\partial}x + \partial z\bar{\partial}z}{z^2}$$

- $\Sigma \setminus \{\varepsilon_i\}$: 3-punctured sphere with worldsheet cut-offs at the punctures $|w - w_i| > \varepsilon_i$
- nontrivial: ε_i is fixed by a **target-space** cut-off $z = \mathcal{E}$
- The first term – regularized 'Pohlmeyer' area – depends on the solution of modified sinh-Gordon, but not on the worldsheet cut-off
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Area:

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2. Pass to the double cover $\widetilde{\Sigma}$ given by $y^2 = T(w)$
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$$d\omega = 0 \qquad d\eta = 0$$

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Regularized 'Pohlmeyer' area

We can use the techniques of Alday, Maldacena, Sever, Vieira to evaluate the regularized 'Pohlmeyer' area (albeit with some twists...)

1. Go to a gauge where Φ_w is diagonal.

$$\Phi_w \longrightarrow \begin{pmatrix} -\frac{\sqrt{T}}{2} & 0 \\ 0 & \frac{\sqrt{T}}{2} \end{pmatrix}$$

2. Pass to the double cover $\widetilde{\Sigma}$ given by $y^2 = T(w)$
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$$\int_{\Sigma_g} \omega \wedge \eta = \sum_{i=1}^{g} \int_{A_i} \omega \int_{B_i} \eta - \int_{A_i} \eta \int_{B_i} \omega$$

But here $\widetilde{\Sigma}$ has genus 0 and punctures...
Moreover the forms have singularities at the punctures *and* at the branch points of the double cover...

6. Generalize the Riemann formula to the present case...
Two ways to proceed:
— redo the proof directly for $\widetilde{\Sigma} \setminus \{singularities\}$ **quite messy...**
— treat the punctures as infinitesimal cuts, use reciprocity for genus 3 and deal only with the singularitites of η at the branch points... easier...

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    c.f. Alday, Maldacena, Sever, Vieira

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$$(*) \qquad \partial\Psi + J_w\Psi = 0 \qquad\qquad \overline{\partial}\Psi + J_{\overline{w}}\Psi = 0$$

characterized by the mondromies

$$e^{\pm i\Delta_k \frac{\pi}{2}\left(\xi - \frac{1}{\xi}\right)} \equiv e^{\pm i\Delta_k \pi \sinh\theta} \equiv e^{\pm i p_k(\theta)} \qquad \text{where} \quad \xi = e^{\theta}$$

- Given two solutions of the linear system $(*)$, Ψ_1^a and Ψ_2^a, one can form the (skew) product

$$\langle \Psi_1 \Psi_2 \rangle \equiv \varepsilon_{ab}\Psi_1^a\Psi_1^b$$

which is a function of the spectral parameter $\xi = e^{\theta}$

- The standard solutions k and $\overline{k}$ are normalized by

$$\langle k\overline{k} \rangle = 1$$

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$$\langle \bar{k} \bar{l} \rangle (\theta) = -\langle k l \rangle (\theta + i\pi) \qquad \langle \bar{k} l \rangle (\theta) = -\langle k \bar{l} \rangle (\theta + i\pi)$$

4. The resulting functional equations can be solved for $\langle k l \rangle (\theta)$!

Overlaps between solutions of the linear system

- We obtain in particular

$$\langle 32 \rangle \langle 32 \rangle^{++} = \frac{\sin \frac{p_1(\theta)-p_2(\theta)-p_3(\theta)}{2} \sin \frac{p_1(\theta)+p_2(\theta)-p_3(\theta)}{2}}{\sin p_2(\theta) \sin p_3(\theta)}$$

  which becomes

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- The basic functional equation to solve is

$$f^+ f^- = 1 - e^{-a\pi \cosh\theta}$$

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$$f(\theta) = \underbrace{e^{Me^{\theta}+\bar{M}e^{-\theta}}}_{\text{zero mode part}} \cdot \exp \int_{-\infty}^{\infty} \frac{d\theta'}{2\pi} \frac{\log\left(1-e^{-a\pi \cosh\theta'}\right)}{\cosh(\theta-\theta')}$$

- The zero-mode constants can be obtained from integrals of $\sqrt{T}$ and $\sqrt{\bar{T}}$

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Recall:

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$$\int_{C_{-11}} \eta = h(2\Delta - \Delta_\infty) + h(2\Delta + \Delta_\infty) - 2h(2\Delta)$$

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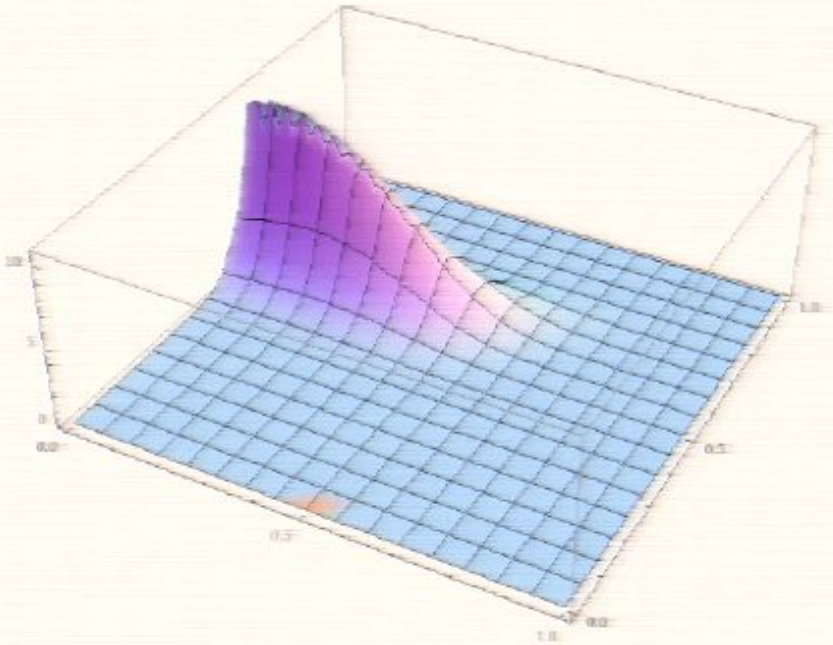
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Numerical check

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Regularized action density



$\Delta = \Delta_\infty = 4.0$

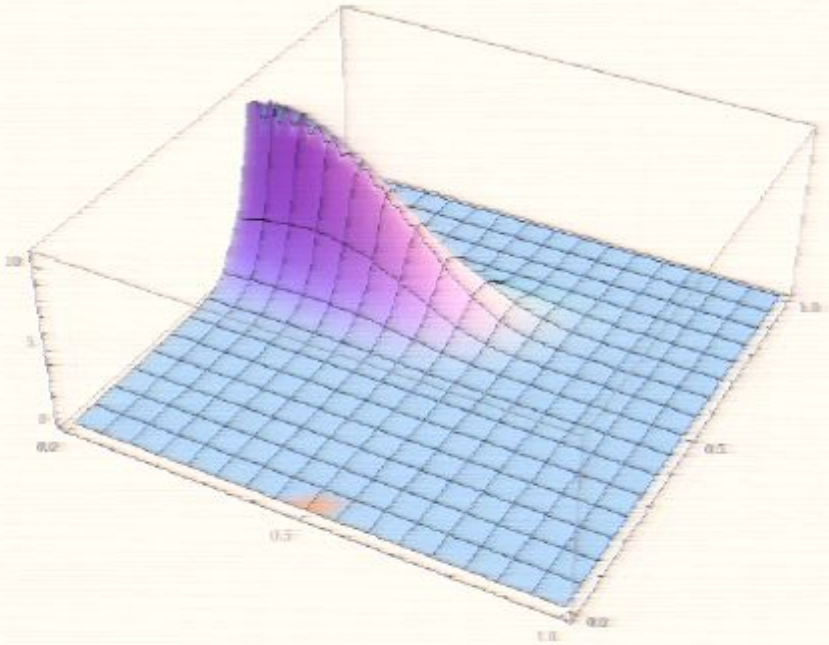
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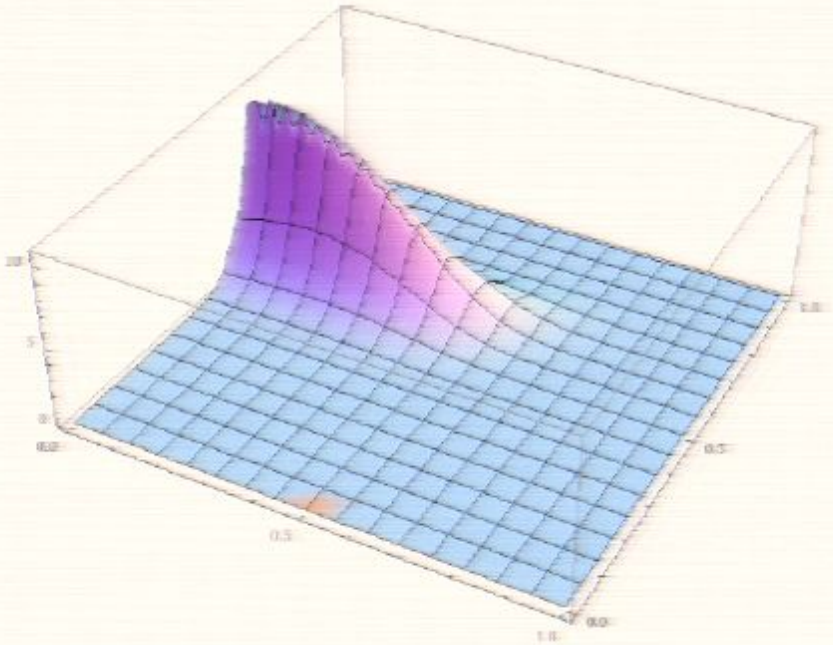
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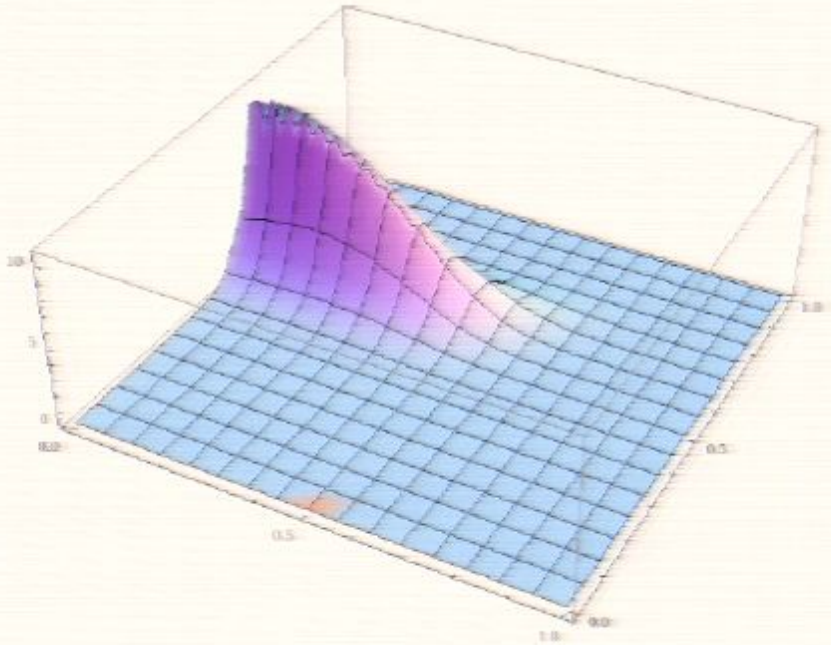
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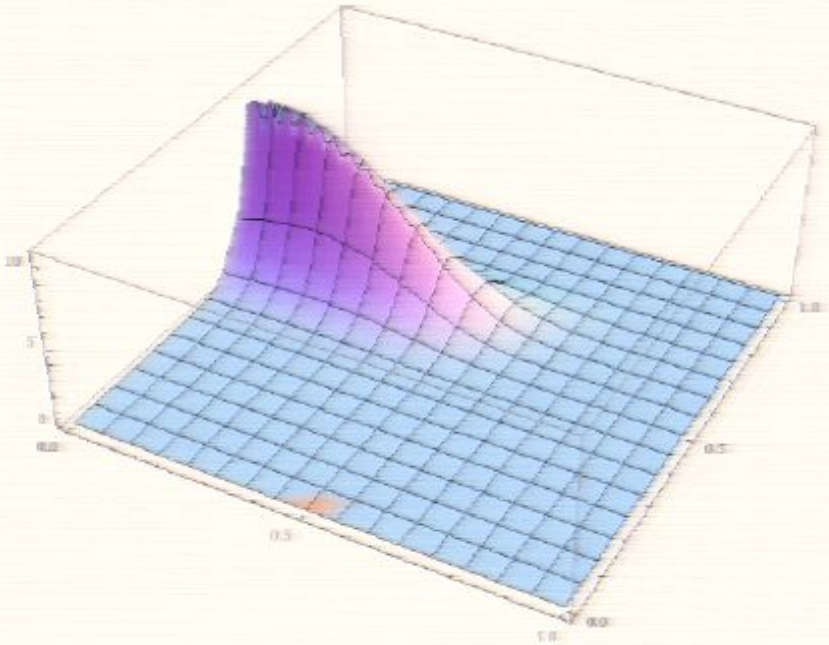
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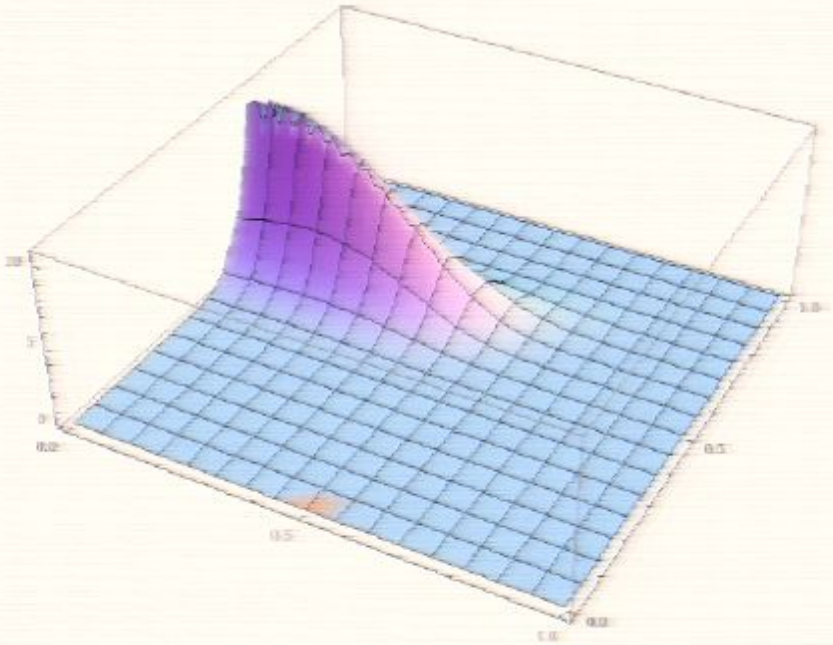
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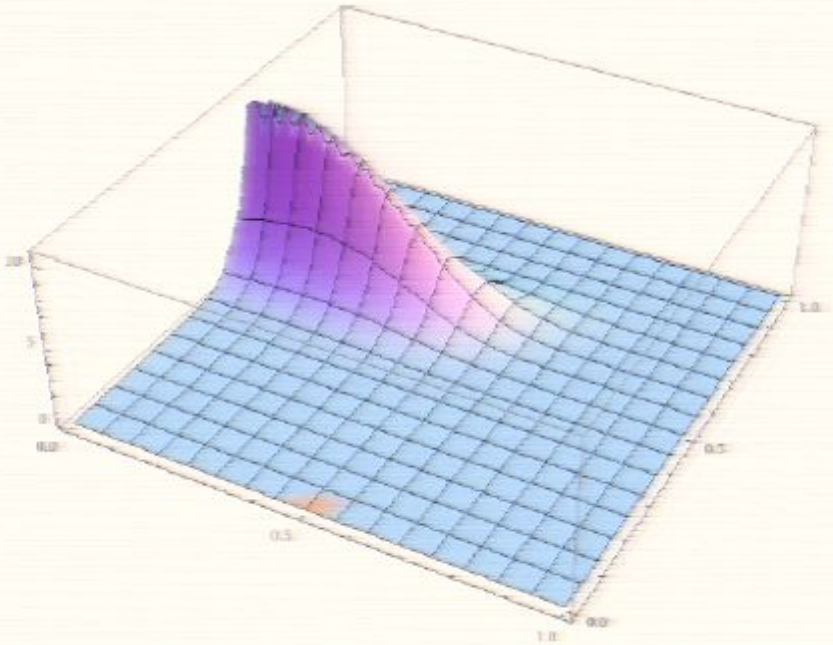
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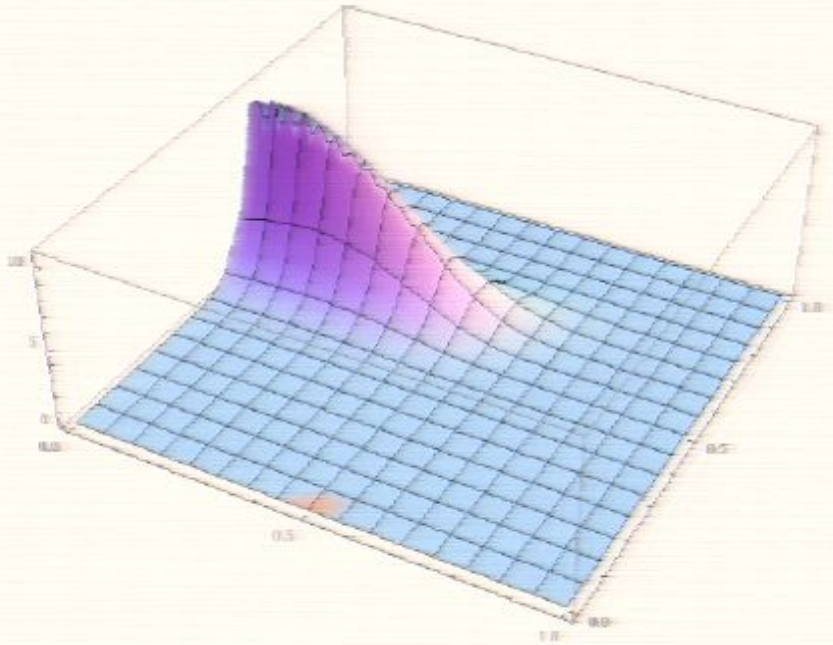
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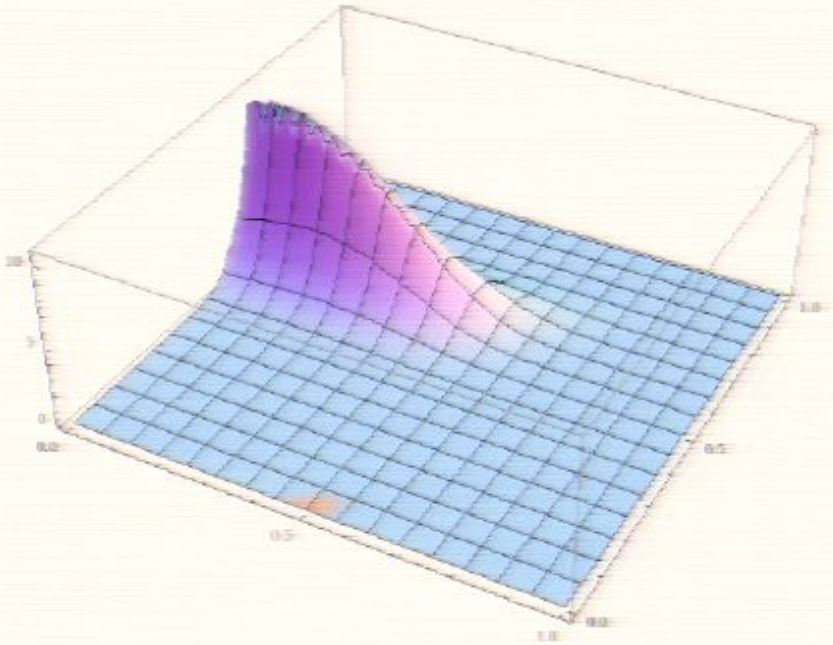
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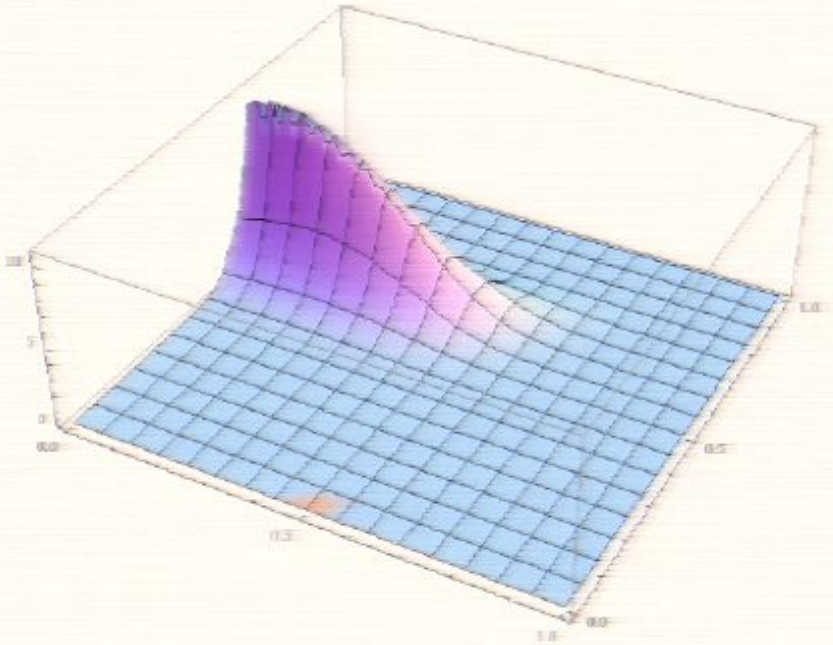
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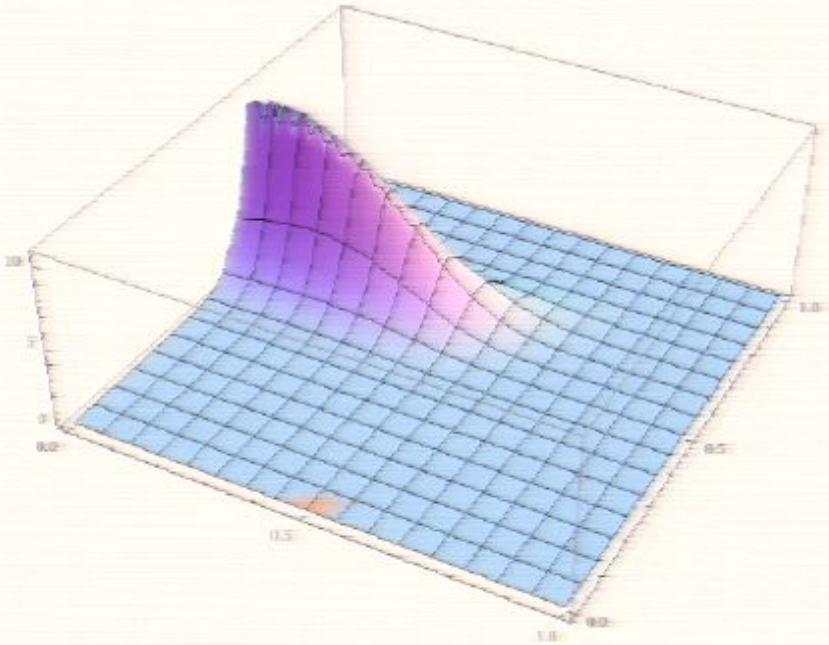
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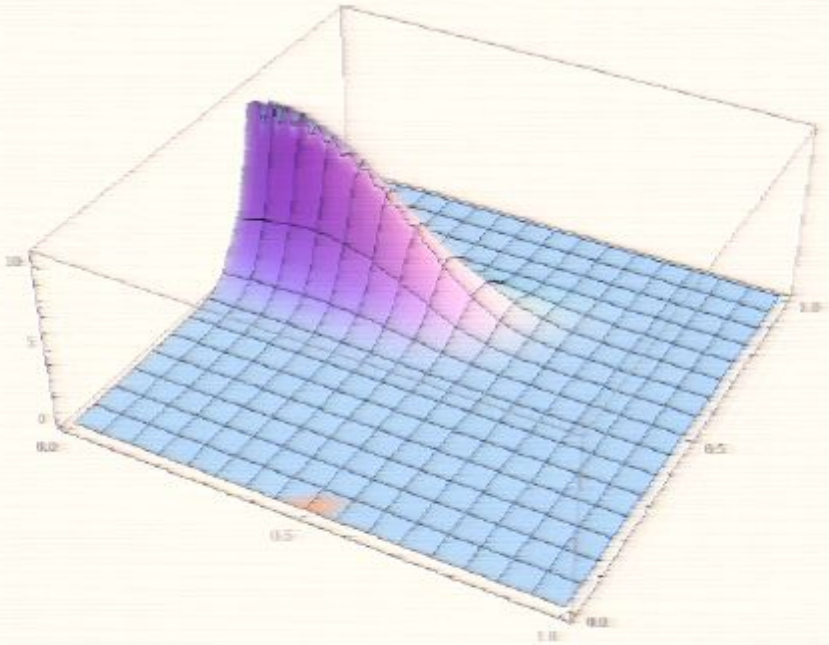
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$$h(a) = \frac{1}{\pi}\int_{-\infty}^{\infty} e^\theta \log\left(1 - e^{-a\pi\cosh\theta}\right) d\theta$$

Numerical check

We have solved the modified sinh-Gordon equations numerically and evaluated the resulting regularized 'Pohlmeyer' area in order to compare with our analytical formula.

Regularized action density



$\Delta = \Delta_\infty = 4.0$

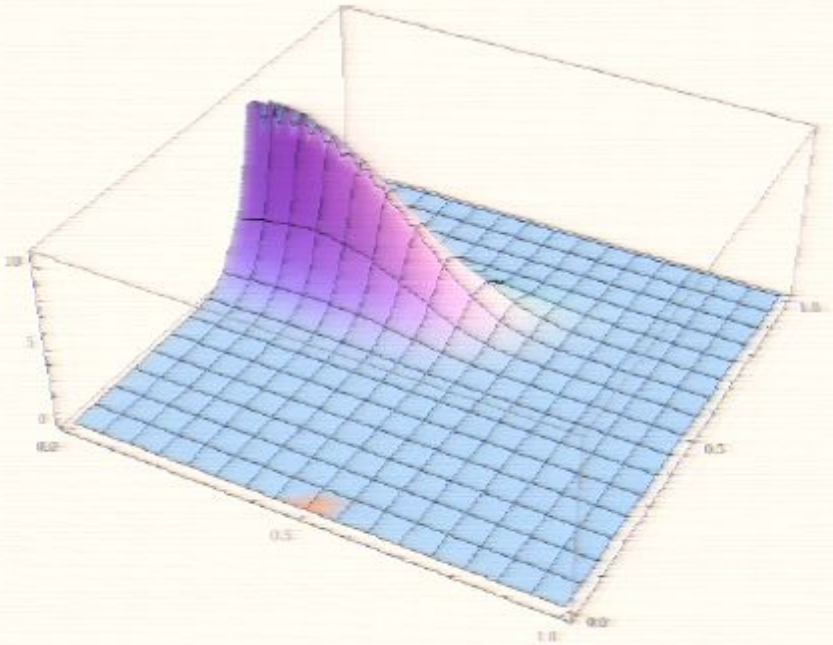
Δ	Δ_∞	numerics	our formula
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0.5	0.9	0.107649	0.107622
1.	1.	0.426311	0.426166
1.	1.05	0.429572	0.429503
2.	2.	0.517689	0.517688
2.	3.	0.488985	0.488985
4.	4.	0.523584	0.523584
4.	7.99	0.0152435	0.0152435

Numerics become more difficult and less reliable for small Δ's

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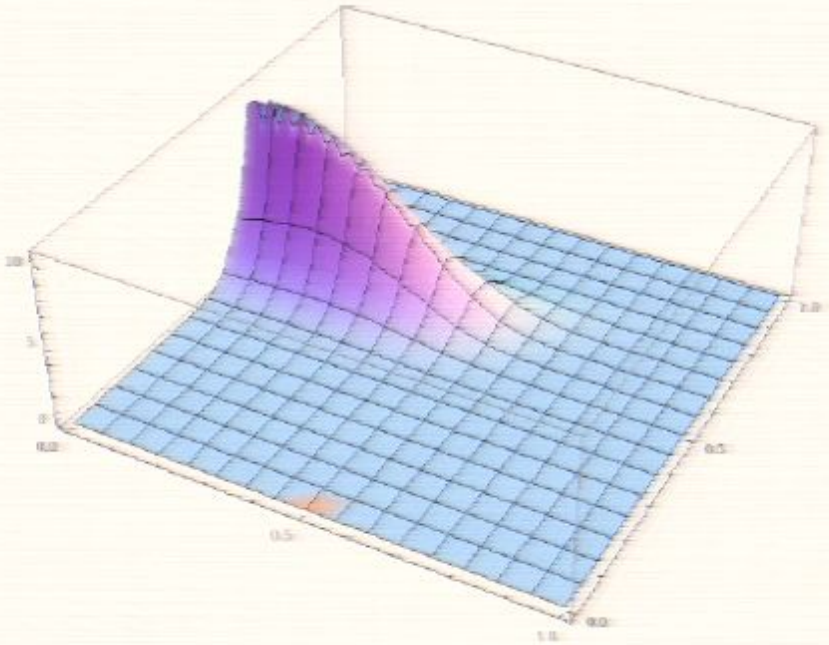
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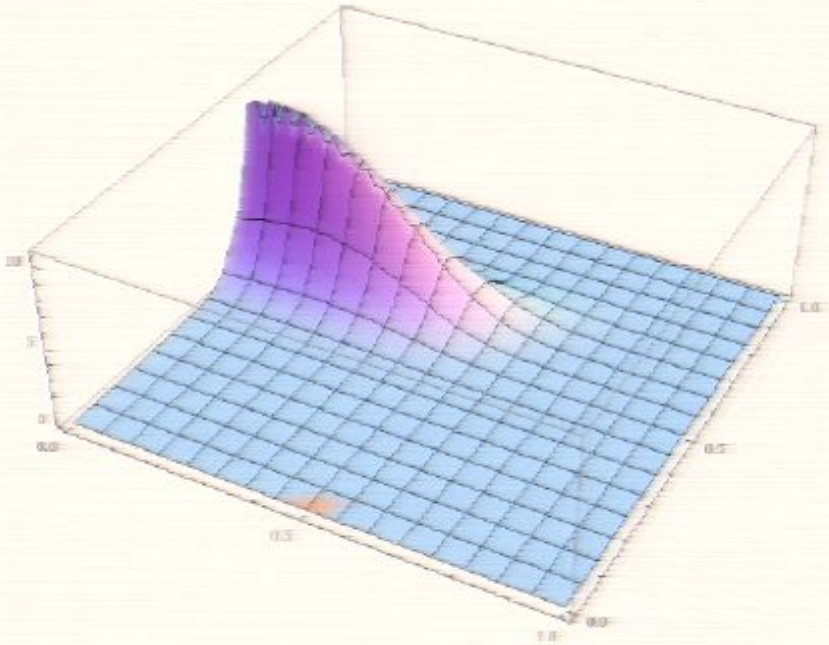
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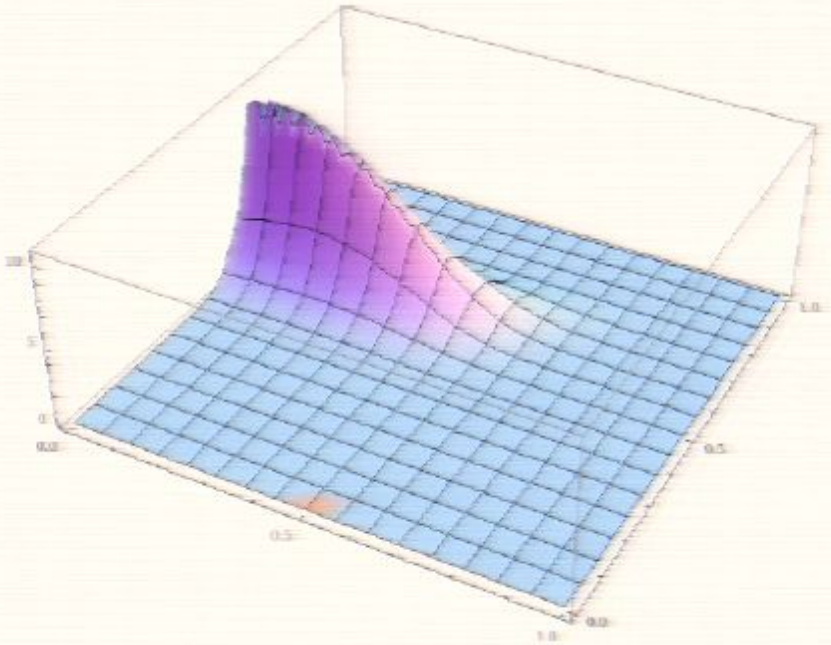
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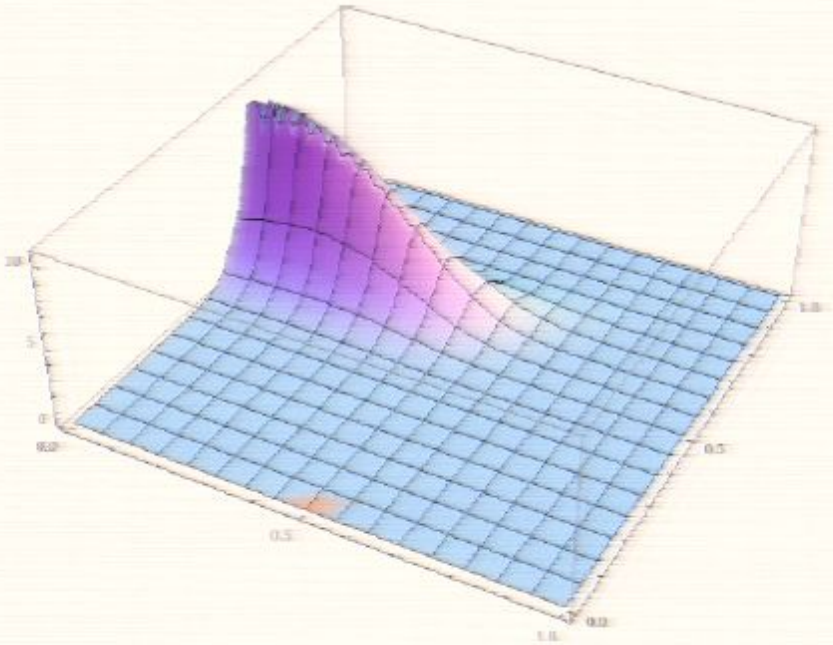
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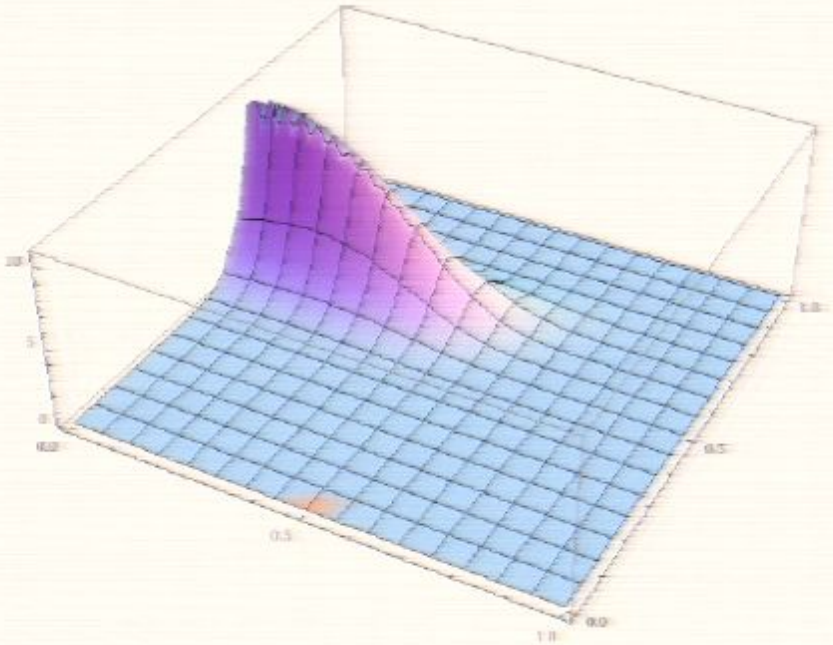
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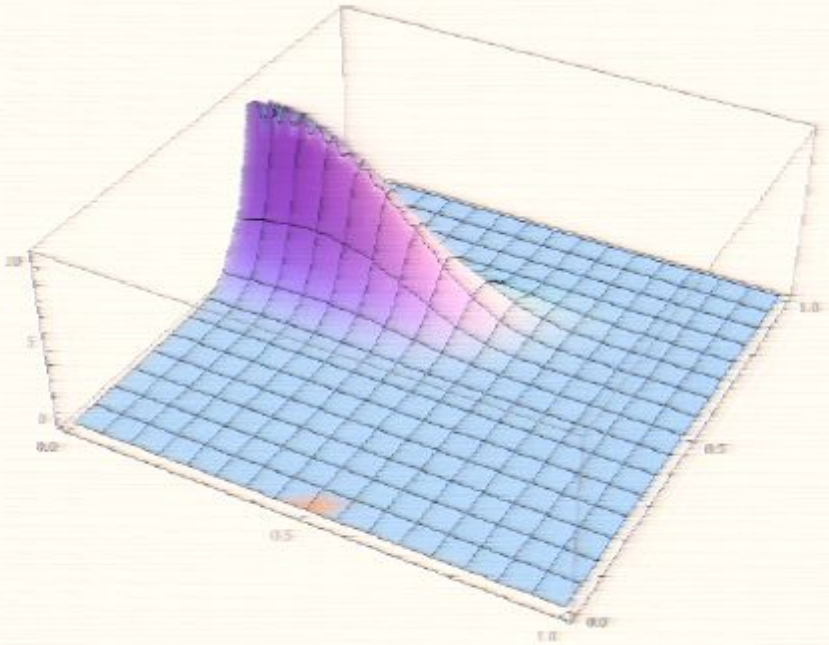
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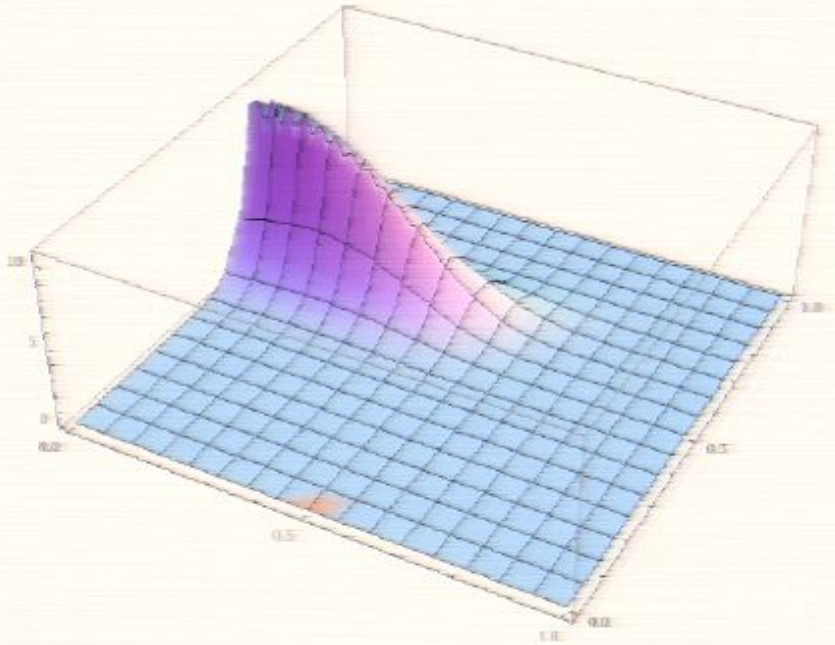
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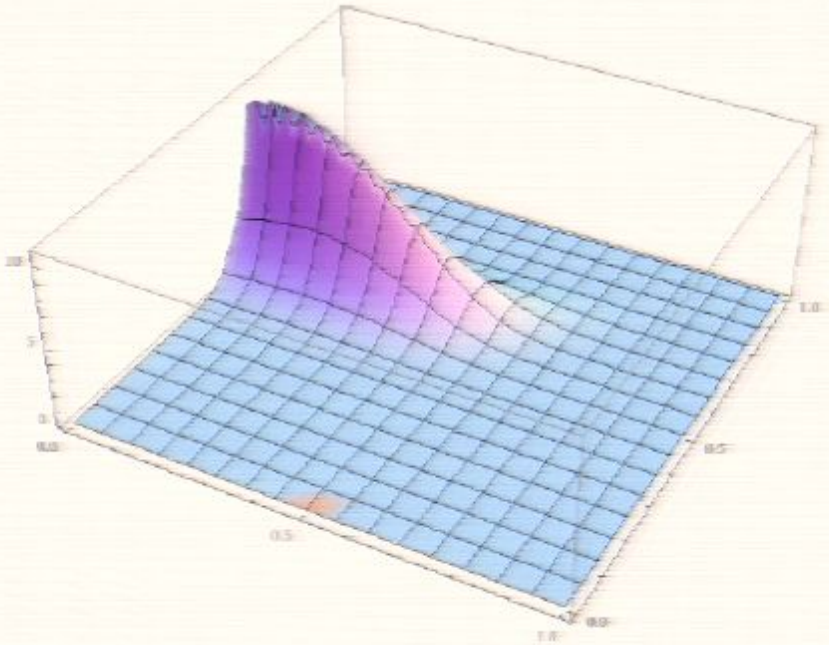
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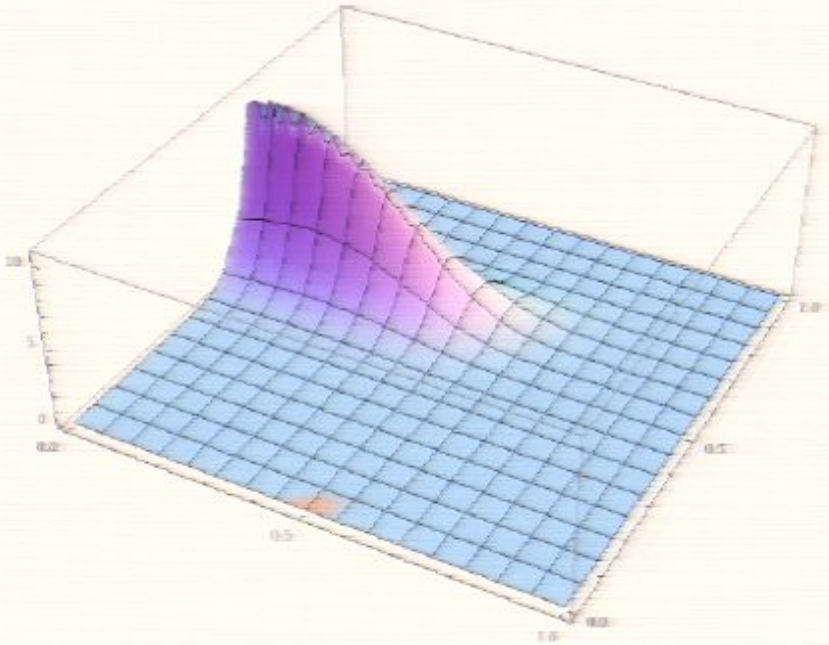
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The cut-off integral

- We have to calculate

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- This integral can be done analytically

$$\int_{\Sigma\setminus\{\varepsilon_i\}} \sqrt{T(w)\overline{T}(\overline{w})}\, d^2w = \mathit{Finite} + \Delta^2 \log \varepsilon_1 + \Delta^2 \log \varepsilon_{-1} + \Delta_\infty^2 \log \varepsilon_\infty$$

where

$$\mathit{Finite} = \pi\left(-\left(\Delta + \frac{\Delta_\infty}{2}\right)^2 \log(2\Delta + \Delta_\infty) - 2\Delta^2 \log \Delta + \ldots\right)$$

- We have to link the worldsheet cut-off's $\varepsilon_1, \varepsilon_{-1}, \varepsilon_\infty$ to the target space cut-off $z = \mathcal{E}$

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- We have to calculate

$$\int_{\Sigma\setminus\{\varepsilon_i\}} \sqrt{T(w)\overline{T}(\overline{w})}\, d^2w$$

- This integral can be done analytically

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normalized by $\langle \Psi_A \Psi_B \rangle = 1$

Then the coordinates of the punctures are encoded in the products at $\theta = 0$

$$x_k = \frac{\langle k\Psi_B \rangle}{\langle k\Psi_A \rangle}$$

and the target-space ($z = \mathcal{E}$) and worldsheet cut-offs are linked by

$$\Delta_k \log \varepsilon_k = \log \left(\mathcal{E} |\langle k\Psi_A \rangle|^2 \right)$$

These expressions are enough to evaluate

$$\Delta^2 \log \varepsilon_1 + \Delta^2 \log \varepsilon_{-1} + \Delta^2_\infty \log \varepsilon_\infty$$

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$\Delta^2 \log \varepsilon_1 + \Delta^2 \log \varepsilon_{-1} + \Delta_\infty^2 \log \varepsilon_\infty$ yields

- The standard spacetime dependence ($\Delta_i \equiv \sqrt{\lambda}\Delta_i$)

$$\frac{1}{\left(\frac{x_{23}}{\varepsilon}\right)^{\Delta_2+\Delta_3-\Delta_1}\left(\frac{x_{13}}{\varepsilon}\right)^{\Delta_1+\Delta_3-\Delta_2}\left(\frac{x_{12}}{\varepsilon}\right)^{\Delta_1+\Delta_2-\Delta_3}}$$

- An additional contribution to the OPE coefficients (all products at $\theta = 0$)

$$-(\Delta_2+\Delta_3-\Delta_1)\log(32)-(\Delta_1+\Delta_3-\Delta_2)\log(13)-(\Delta_1+\Delta_2-\Delta_3)\log(12)$$

with the products given by the solution of the functional equations

- The zero-mode part of $\langle kl \rangle$ **exactly cancels** the remaining *Finite* part of $\int_{\Sigma\setminus\{\varepsilon_i\}} \sqrt{T(w)\overline{T}(\overline{w})}$
- We obtain, however, a nonzero contribution from the nontrivial part of $\langle kl \rangle$

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Final answer

The final answer for the OPE coefficient is a product of the currently unknown regularized S^5 contribution

$$\underbrace{\exp \frac{\sqrt{\lambda}}{2} \int_\Sigma S^5 \text{ contribution} - \sqrt{T(w)\overline{T}(w)}\, d^2w}_{\text{Unknown but finite!}}$$

and the explicit AdS answer

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$\Delta^2 \log \varepsilon_1 + \Delta^2 \log \varepsilon_{-1} + \Delta_\infty^2 \log \varepsilon_\infty$ yields

1. The standard spacetime dependence ($\mathbf{\Delta}_i \equiv \sqrt{\lambda}\Delta_i$)

$$\frac{1}{\left(\frac{x_{23}}{\mathcal{E}}\right)^{\mathbf{\Delta}_2+\mathbf{\Delta}_3-\mathbf{\Delta}_1}\left(\frac{x_{13}}{\mathcal{E}}\right)^{\mathbf{\Delta}_1+\mathbf{\Delta}_3-\mathbf{\Delta}_2}\left(\frac{x_{12}}{\mathcal{E}}\right)^{\mathbf{\Delta}_1+\mathbf{\Delta}_2-\mathbf{\Delta}_3}}$$

2. An additional contribution to the OPE coefficients (all products at $\theta = 0$)

$$-(\Delta_2+\Delta_3-\Delta_1)\log\langle 32\rangle - (\Delta_1+\Delta_3-\Delta_2)\log\langle 13\rangle - (\Delta_1+\Delta_2-\Delta_3)\log\langle 12\rangle$$

with the products given by the solution of the functional equations

3. The zero-mode part of $\langle kl\rangle$ **exactly cancels** the remaining *Finite* part of $\int_{\Sigma\setminus\{\varepsilon_i\}} \sqrt{T(w)\overline{T}(\overline{w})}$

4. We obtain, however, a nonzero contribution from the nontrivial part of $\langle kl\rangle$

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Comments:

- In the extremal limit $\Delta_\infty = 2\Delta$ we obtain 1 (the 1/6 is crucial here)
- For large Δ, $\tilde{h}(a) \propto e^{-\pi a}$ and the AdS contribution approaches a constant

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this limit ($\sim C_{MMM}$) coincides with the expression in [Klose, McLoughlin]

Caution: The regularized S^5 contributions have to be added to these expressions to get the full OPE coefficients

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- In the extremal limit $\Delta_\infty = 2\Delta$ we obtain 1 (the $1/6$ is crucial here)
- For large Δ, $\tilde{h}(a) \propto e^{-\pi a}$ and the AdS contribution approaches a constant

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Final answer

$$\exp\left\{-\frac{\sqrt{\lambda}}{6}-\sqrt{\lambda}\left[(2\Delta-\Delta_\infty)\tilde{P}_{-11}+2\Delta_\infty\tilde{P}_{1\infty}\right]\right\}$$

Comments:

- In the extremal limit $\Delta_\infty = 2\Delta$ we obtain 1 (the $1/6$ is crucial here)
- For large Δ, $\tilde{h}(a) \propto e^{-\pi a}$ and the AdS contribution approaches a constant

$$e^{-\frac{\sqrt{\lambda}}{6}}$$

- For small Δ, $\tilde{h}(a) \sim -\frac{1}{6a}-\frac{1}{2}\log a$. Then we get ($\boldsymbol{\Delta} \equiv \sqrt{\lambda}\Delta$)

$$\left(\frac{(2\Delta-\Delta_\infty)^{2\boldsymbol{\Delta}-\boldsymbol{\Delta}_\infty}(2\Delta+\Delta_\infty)^{2\boldsymbol{\Delta}+\boldsymbol{\Delta}_\infty}\Delta_\infty^{2\boldsymbol{\Delta}_\infty}}{(2\Delta)^{4\boldsymbol{\Delta}}(2\Delta_\infty)^{2\boldsymbol{\Delta}_\infty}}\right)^{\frac{1}{2}}$$

this limit ($\sim C_{MMM}$) coincides with the expression in [Klose, McLoughlin]

Caution: The regularized S^5 contributions have to be added to these expressions to get the full OPE coefficients

$$\Delta^2 \log \varepsilon_1 + \Delta^2 \log \varepsilon_{-1} + \Delta_\infty^2 \log \varepsilon_\infty \qquad \text{yields}$$

1. The standard spacetime dependence ($\boldsymbol{\Delta}_i \equiv \sqrt{\lambda}\Delta_i$)

$$\frac{1}{\left(\frac{x_{23}}{\mathcal{E}}\right)^{\boldsymbol{\Delta}_2+\boldsymbol{\Delta}_3-\boldsymbol{\Delta}_1}\left(\frac{x_{13}}{\mathcal{E}}\right)^{\boldsymbol{\Delta}_1+\boldsymbol{\Delta}_3-\boldsymbol{\Delta}_2}\left(\frac{x_{12}}{\mathcal{E}}\right)^{\boldsymbol{\Delta}_1+\boldsymbol{\Delta}_2-\boldsymbol{\Delta}_3}}$$

2. An additional contribution to the OPE coefficients (all products at $\theta = 0$)

$$-(\Delta_2+\Delta_3-\Delta_1)\log(32)-(\Delta_1+\Delta_3-\Delta_2)\log(13)-(\Delta_1+\Delta_2-\Delta_3)\log(12)$$

with the products given by the solution of the functional equations

3. The zero-mode part of $\langle kl \rangle$ **exactly cancels** the remaining *Finite* part of $\int_{\Sigma\setminus\{\varepsilon_i\}} \sqrt{T(w)\overline{T}(\overline{w})}$

4. We obtain, however, a nonzero contribution from the nontrivial part of $\langle kl \rangle$

The cut-off integral

- We have to calculate

$$\int_{\Sigma\setminus\{\varepsilon_i\}} \sqrt{T(w)\overline{T}(\overline{w})}\, d^2w$$

- This integral can be done analytically

$$\int_{\Sigma\setminus\{\varepsilon_i\}} \sqrt{T(w)\overline{T}(\overline{w})}\, d^2w = Finite + \Delta^2 \log \varepsilon_1 + \Delta^2 \log \varepsilon_{-1} + \Delta_\infty^2 \log \varepsilon_\infty$$

where

$$Finite = \pi\left(-\left(\Delta + \frac{\Delta_\infty}{2}\right)^2 \log(2\Delta + \Delta_\infty) - 2\Delta^2 \log \Delta + \ldots\right)$$

- We have to link the worldsheet cut-off's $\varepsilon_1, \varepsilon_{-1}, \varepsilon_\infty$ to the target space cut-off $z = \mathcal{E}$