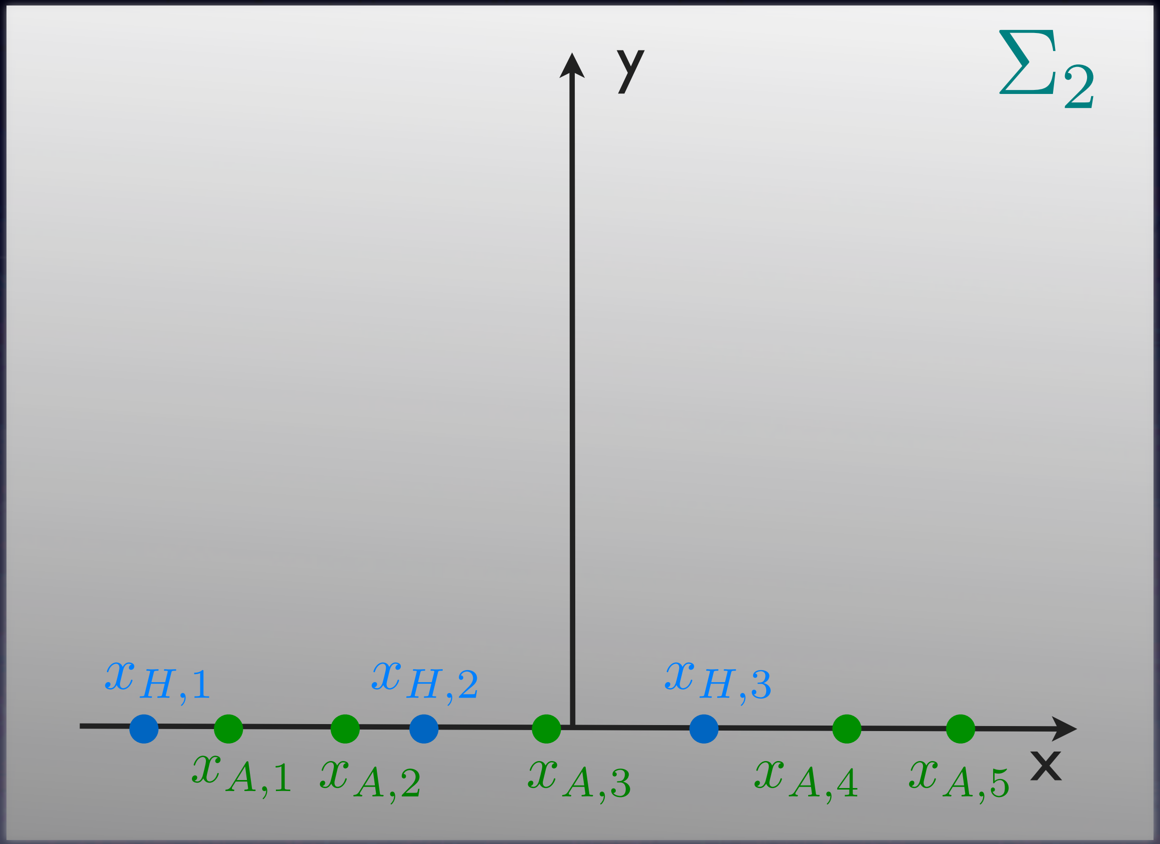
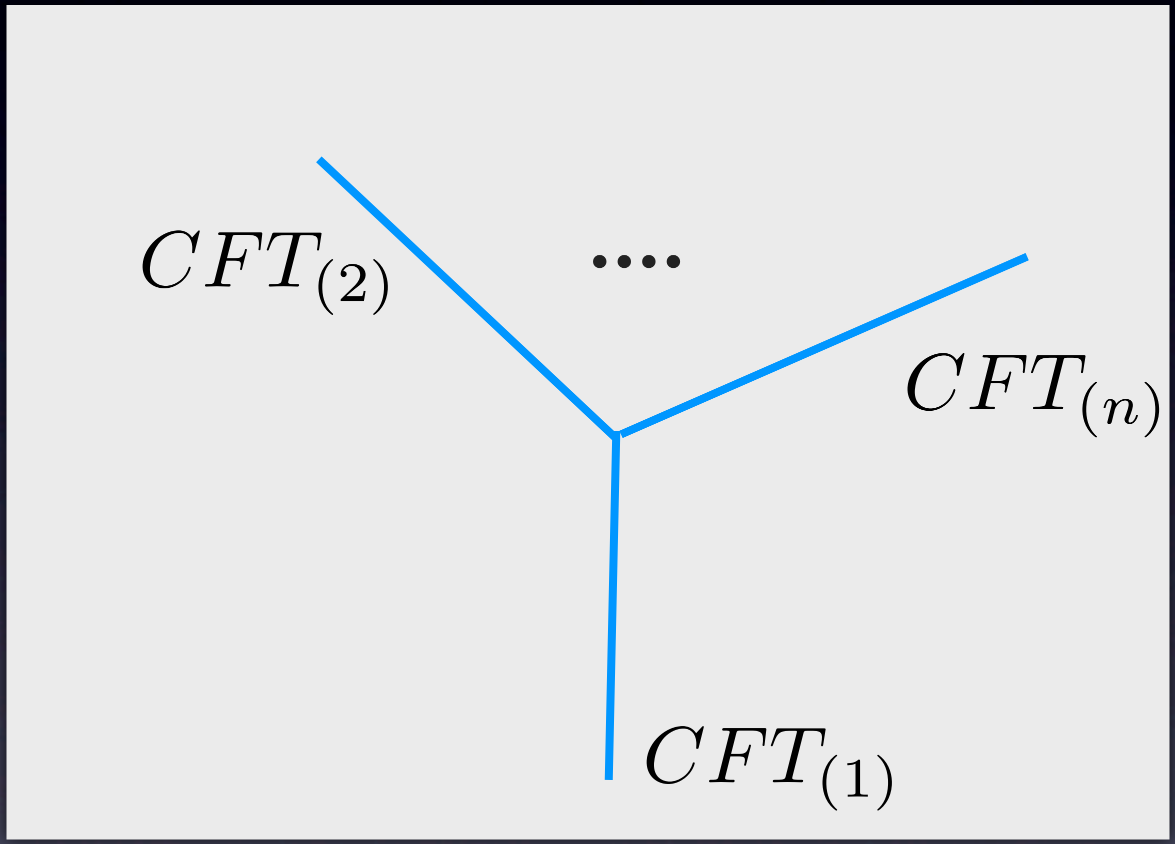
Holographic duals of interface theories and junctions of CFTs





Plan of the talk

- Interfaces and junctions in CFT
- Holographic interface solutions
- Half-BPS Janus solution
- Calculation of boundary entropy
- Multi-Janus solutions
- Conclusions

Based on:

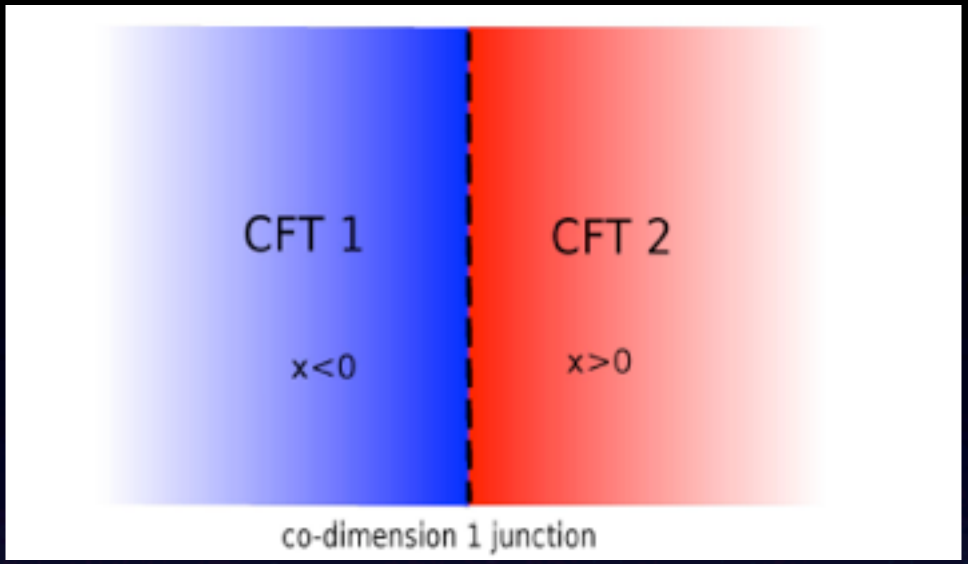
"Half-BPS Solutions locally asymptotic to $AdS_3 \times S^3$ and interface conformal field theories" by M. Chiodaroli, M. Gutperle and D. Krym, arXiv: 0910.0466

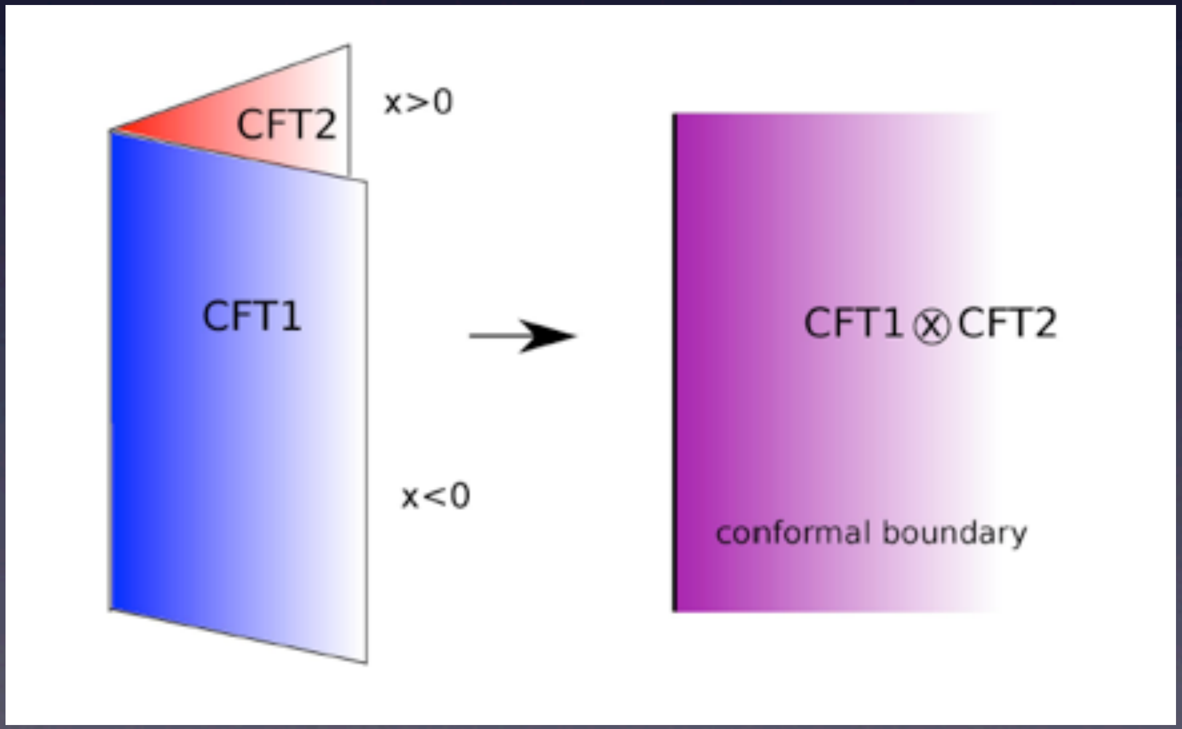
"Boundary Entropy of supersymmetric Janus solutions" by M. Chiodaroli, Ling-Yan Hung and M. Gutperle, arXiv: 1005.4433

Work in progress by M. Chiodaroli, M. Gutperle, Ling-Yan Hung, D. Krym and Brian Shieh

Interfaces and junctions in CFT

A conformal interface is a junction betwen two CFTs preserving part of the conformal symmetry. Gluing conditions need to be scale invariant. In 2d continuity of T_{xt} across the interface is sufficient.





The folding trick relates interface CFT's to boundary CFT:
conformal boundary conditions (open string description)

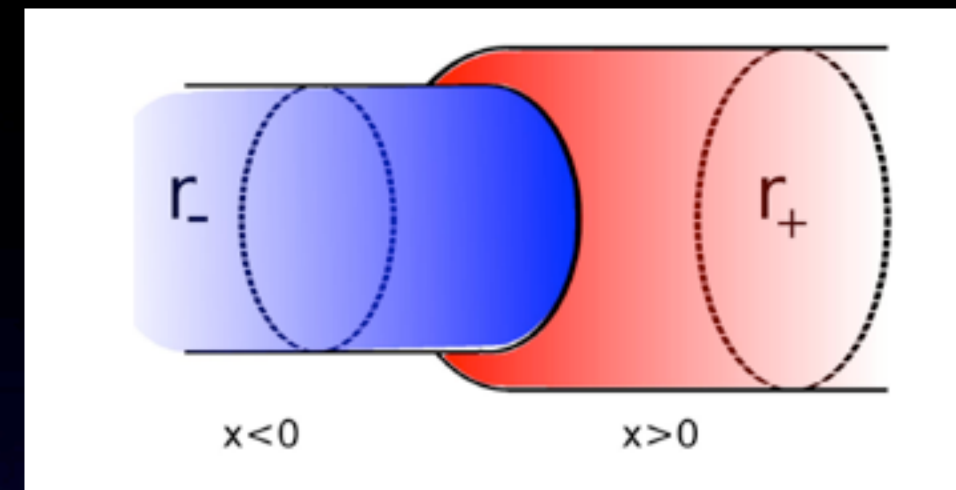
$\leftrightarrow$

conformal boundary state $|| B\rangle$
(closed string description)

Affleck and Ludwig;
Bachas, de Boer, Dijkgraaf and Ooguri

Interfaces and junctions in CFT

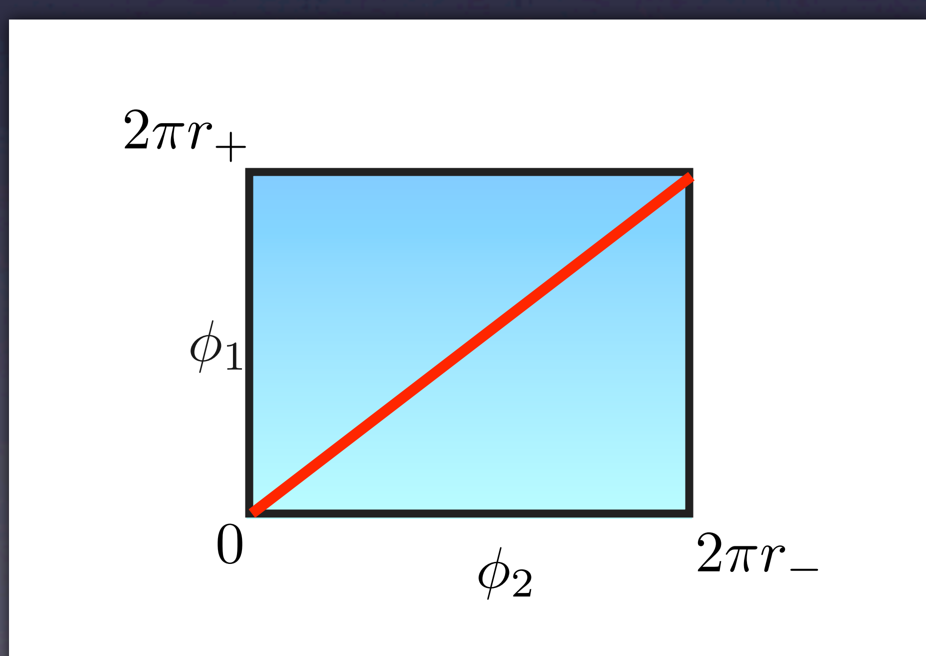
Toy model: compact boson $\phi \sim \phi + 2\pi$
with a jump in the coupling



$$S = 2r_-^2 \int_{x<0} dtdx\ \partial_a \phi \partial^a \phi + 2r_-^2 \int_{x<0} dtdx\ \partial_a \phi \partial^a \phi$$

After rescaling the bosons have a jump in the compactification radius

$$\phi \sim \phi + 2\pi r_\pm$$



After folding one has 2 bosons

$$\phi_1 \sim \phi_1 + 2\pi r_+$$
$$\phi_2 \sim \phi_2 + 2\pi r_-$$

Conformal boundary conditions correspond to a diagonal D1 brane in a 2 torus spanned by $\phi_{1,2}$

Bachas, de Boer, Dijkgraaf and Ooguri

Interfaces and junctions in CFT

Basic quantities which can be calculated for interface CFT's:

- g-factor $g = \langle 0 \,||\, B \rangle$ and boundary entropy $S_{bd} = \ln g$ which measures the ground state degeneracy of the interface

$$g = \frac{1}{\sqrt{2}} \sqrt{\frac{r_+}{r_-} + \frac{r_-}{r_+}}$$

Affleck and Ludwig

- Reflection and transmission coefficients for scattering off the interface

$$\mathcal{R} = \frac{r_-^2 - r_+^2}{r_-^2 + r_+^2}$$

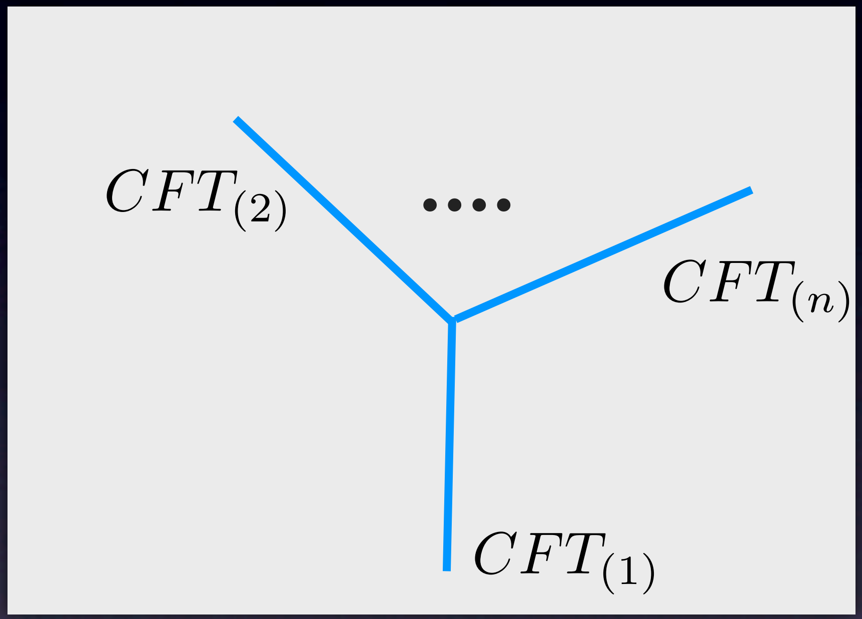
- Casimir energy between two interfaces

Bachas, de Boer, Dijkgraaf and Ooguri

Interfaces and junctions in CFT

Generalizations

Interfaces between 2 CFTs can be generalized to junctions of 3 or more CFTs, for example a star graph:

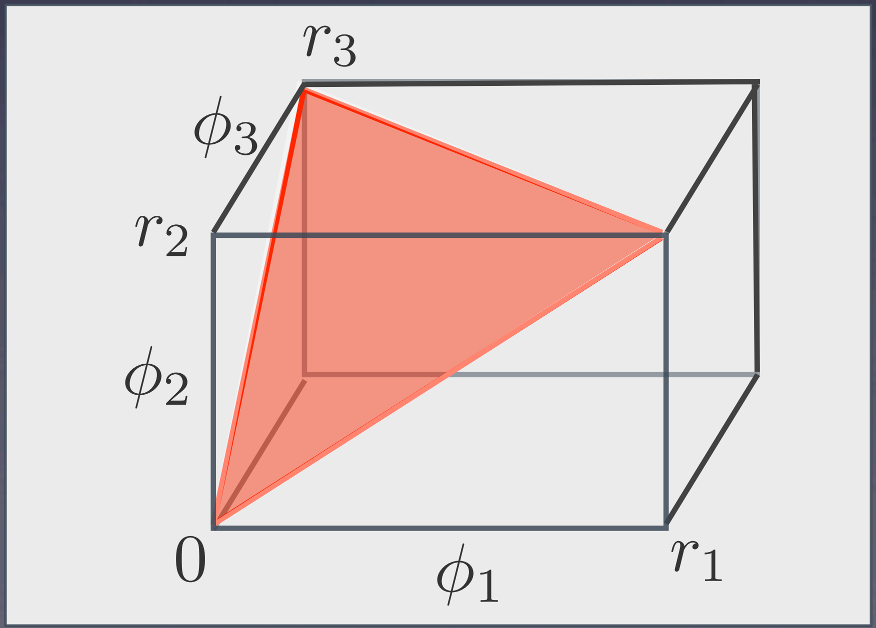


conformal boundary conditions

$$\sum_i T^{(i)}_{xt} = 0$$

n bosons ϕ_i with radius r_i : junction of n quantum wires (with different LL couplings)

Bellazinni, Mintchev and Sorba
Affleck, Chamon and Oshikawa



conformal boundary conditions:
p dim D brane in n-torus
g-factors calculated in BCFT

Interfaces and junctions in CFT

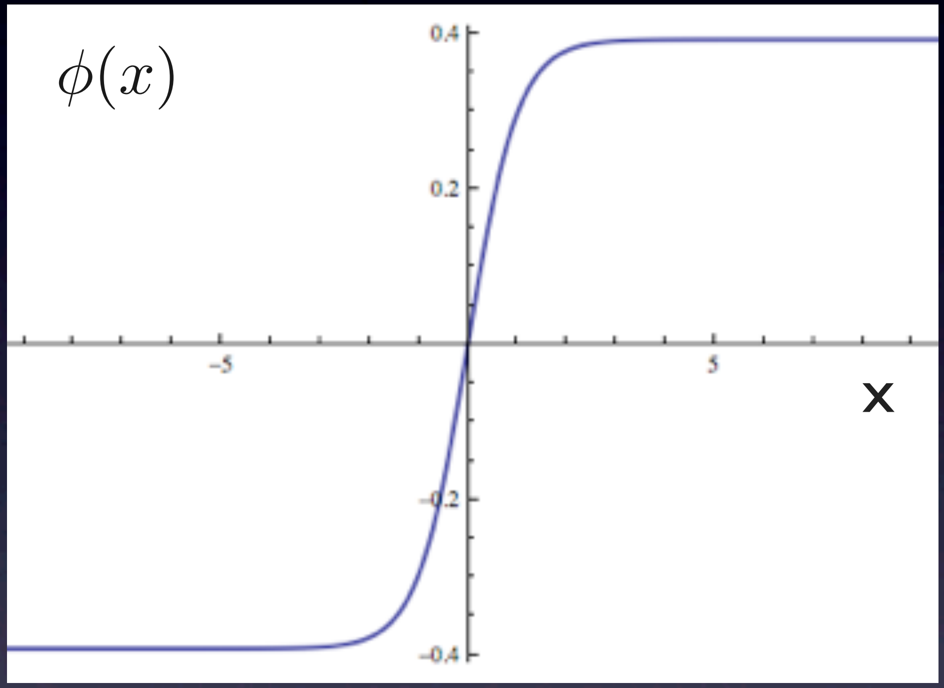
Applications of interface CFT:

- Impurity problems in 1+1 dimensions. Interaction of bulk CFT with an impurity which preserves conformal invariance
- Kondo effect
- Topological interfaces, classification, fusion of interfaces Bachas and Brunner
- Compact bosons give the effective description of interacting fermions systems in 1+1 dimensions via the theory of Luttinger liquids (Radius is related to the coupling constant in the LL).
- Hence interface CFT describe junctions of (critical) quantum wires. Questions like calculation of conductance, tunneling etc can be answered using CFT. Affleck et al.

Goal: Provide a holographic dual description of interface CFT's using AdS_3/CFT_2

Holographic interface solutions

Janus solution: holographic description of a codimenion 1 conformal interface in AdS_{d+1} preserve SO(2,d-1) of SO(2,d) symmetry: Use AdS_d slicling of AdS_{d+1}



$$ds^2 = dx^2 + f(x) ds^2_{AdS_d} \qquad \phi = \phi(x)$$

as $x \to \pm\infty$ the dilaton $\phi \to \phi_\pm$

conformal boundary: divergence of conformal factor of the metric $x \to \pm\infty$

$$ds^2 = dx^2 + \frac{e^{2|x|}}{\xi^2}\big(- dt^2 + dx_1^2 + \cdots + dx_{d-2}^2 + d\xi^2\big) + o(e^{-2|x|})$$

Divergence in three limits $x \to \pm\infty$ and $\xi \to 0$

Holographic interface solutions

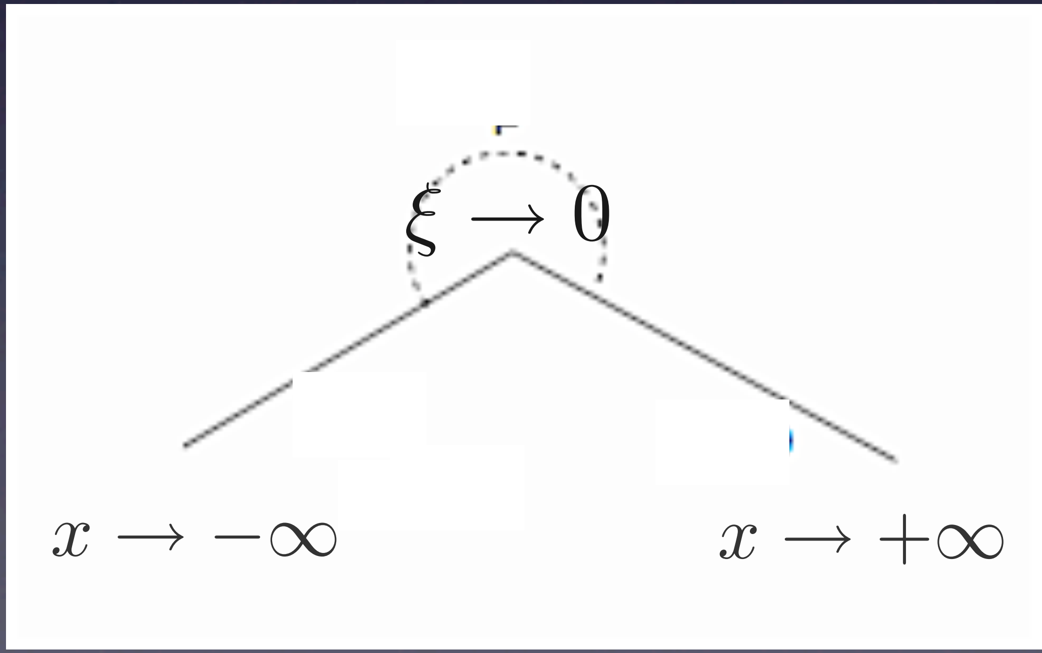
$$ds^2 = dx^2 + \frac{e^{2|x|}}{\xi^2}\left(- dt^2 + dx_1^2 + \cdots + dx_{d-2}^2 + d\xi^2\right) + o(e^{-2|x|})$$

as $x \to \pm\infty$ the boundary is $R^{1,d-2} \times R_+$ spanned by $t, x_1, \cdots, x_{d-2}$

and $\xi \in [0, \infty]$

as $\xi \to 0$ the boundary is $R^{1,d-1}$ and distances in x shrink to zero

In Poincare coordinates the spatial section of the boundary consists of two d-1 dimensional half planes joined by a d-2 dimensional interface.



(complicated) map to Fefferman-Graham coordinates possible

Skenderis and Papadimitriou

Holographic interface solutions

Solution of type IIB superstring theory locally asymptotic $AdS_3 \times S_3 \times K_3$

Ansatz: $AdS_2 \times S^2 \times K_3$ fibration over Riemann surface Σ_2

- $AdS_3 \times S^3$ has global bosonic symmetry $SO(2,2) \times SO(4)$
- 1 dim conformal defect preserves $SO(2,1)$ corresp. to AdS_2
- Superconformal defect preserves 8 of the 16 supersymmetries: type II solution should have 8 unbroken susys
- SO(4) R-symmetry is reduced to SO(3) corresp. to S^2 express three sphere as a fibration of a two sphere over an interval $y \in [0, \pi]$ Susy-Janus ansatz depends on two coordinates x,y

Holographic interface solutions

Bosonic fields of type IIB supergravity depend only on Σ and are consistent with SO(2,1) x SO(3) symmetry

metric: $$ds^2 = f_1^2 ds^2_{AdS_2} + f_2^2 ds^2_{S^2} + f_3^2 ds^2_{K_3} + \rho^2 dz d\bar{z}$$

$i = 0, 1$ $\quad j = 2, 3$ $\quad k = 4, \cdots, 7$ $\quad a = 8, 9$

dilaton/axion: $$Q = q_a e^a, \quad P = P_a e^a$$

complex 3-form: $$G = g_a^{(1)} e^{a01} + g_a^{(2)} e^{a23}$$

AdS_2 $\quad S^2$

Self-dual 5 form: $$F_5 = h_a e^{a0123} + \tilde{h}_a e^{a4567}$$

$AdS_2 \times S^2$ $\quad K_3$

Holographic interface solutions

Susy variation of dilatino and gravitino vanishes for unbroken susy

$$\delta\lambda = i(\Gamma\cdot P)\mathcal{B}^{-1}\varepsilon^* - \frac{i}{24}(\Gamma\cdot G)\varepsilon$$

$$\delta\psi_M = D_\mu\varepsilon + \frac{i}{480}(\Gamma\cdot F_{(5)})\Gamma_\mu\varepsilon - \frac{1}{96}\left(\Gamma_\mu(\Gamma\cdot G) + 2(\Gamma\cdot G)\Gamma_\mu\right)\mathcal{B}^{-1}\varepsilon^*$$

Expand ϵ in terms of Killing spinors on $AdS_2\times S^2\times K^3$

$$\epsilon = \sum_{\eta_1,\eta_2}\chi_{\eta_1,\eta_2,\eta_3}\otimes\xi_{\eta_1,\eta_2,\eta_3}$$

2 dim spinors on Σ

Use discrete symmetries of the equation to reduce BPS equations to a single 2 dim spinor ξ

Solution of reduced BPS equations give 8 unbroken susys in terms of 2 harmonic and 2 holomorphic functions on Σ

Holographic interface solutions

Local solution: All bosonic fields are expressed in term of
2 holomorphic functions $A(z), B(z)$
2 harmonic functions $H(z,\bar z), K(z,\bar z)$
Satisfies all equations of motion and Bianchi identities of type II B supergravity

axion/dilaton:

$$e^{4\Phi} = \frac{1}{4}\Big(A+\bar A-\frac{(B+\bar B)^2}{K}\Big)\Big(A+\bar A-\frac{(B-\bar B)^2}{K}\Big)$$

$$\chi = \frac{1}{2i}\Big(\frac{B^2-\bar B^2}{K}-A+\bar A\Big)$$

metric:

$$f_1^2 = \frac{e^{-2\Phi}}{2f_3^2}\frac{|H|}{K}\Big((A+\bar A)K-(B-\bar B)^2\Big)$$

$$f_3^2 = \frac{e^{-2\Phi}}{2f_3^2}\frac{|H|}{K}\Big((A+\bar A)K-(B+\bar B)^2\Big)$$

$$f_3^4 = \frac{4e^{2\Phi}K}{A+\bar A}$$

With similar formulae for ρ and the AST fields

Holographic interface solutions

Globally regular solutions: All metric factors and physical fields are real, no curvature singularities. Imposes conditions on the harmonic functions

- Riemann surface Σ has boundary $\partial\Sigma$ where sphere closes off, i.e. the metric factor $f_2 \to 0$
- Harmonic functions satisfy Dirichlet boundary conditions on the boundary, except for simple poles

$$K = (A + \bar{A}) = (B + \bar{B}) = H = 0 \qquad \text{on} \quad \partial\Sigma$$

- Singularities (simple poles) of harmonic functions only at the boundaries
- Several other conditions (see arXiv: 0910.0466)

Holographic interface solutions

Counting of moduli of regular solution on the half plane

$$H = i\sum_{i=1}^{n}\frac{c_{H,i}}{u-x_{H,i}} + c.c.$$

n-3 positions of poles , n residues: SL (2,R) fixes three positions

$$A = i\sum_{i=1}^{2n-2}\frac{c_{A,i}}{u-x_{A,i}} + ib$$

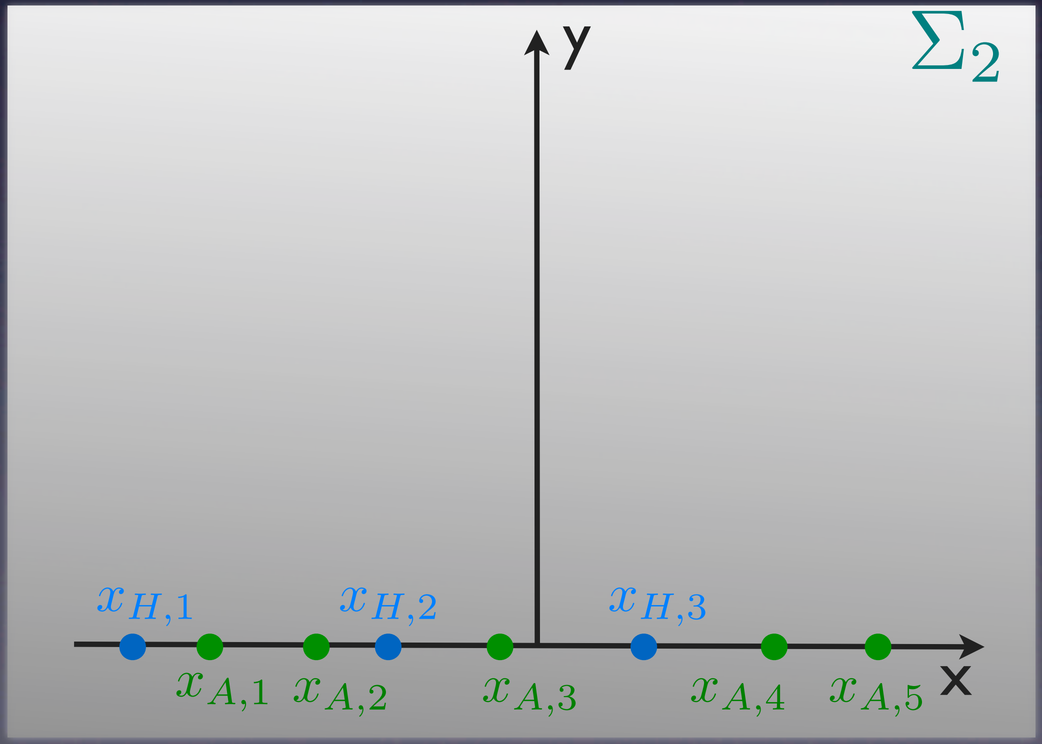
2n-2 positions of poles , 2n+2 residues, one constant

$$B = B_0\frac{\prod_{i=1}^{n-1}(u-x_{H,i})^2}{\prod_{i=1}^{2n-2}(u-x_{A,i})}\partial_u H$$

1 overall constant

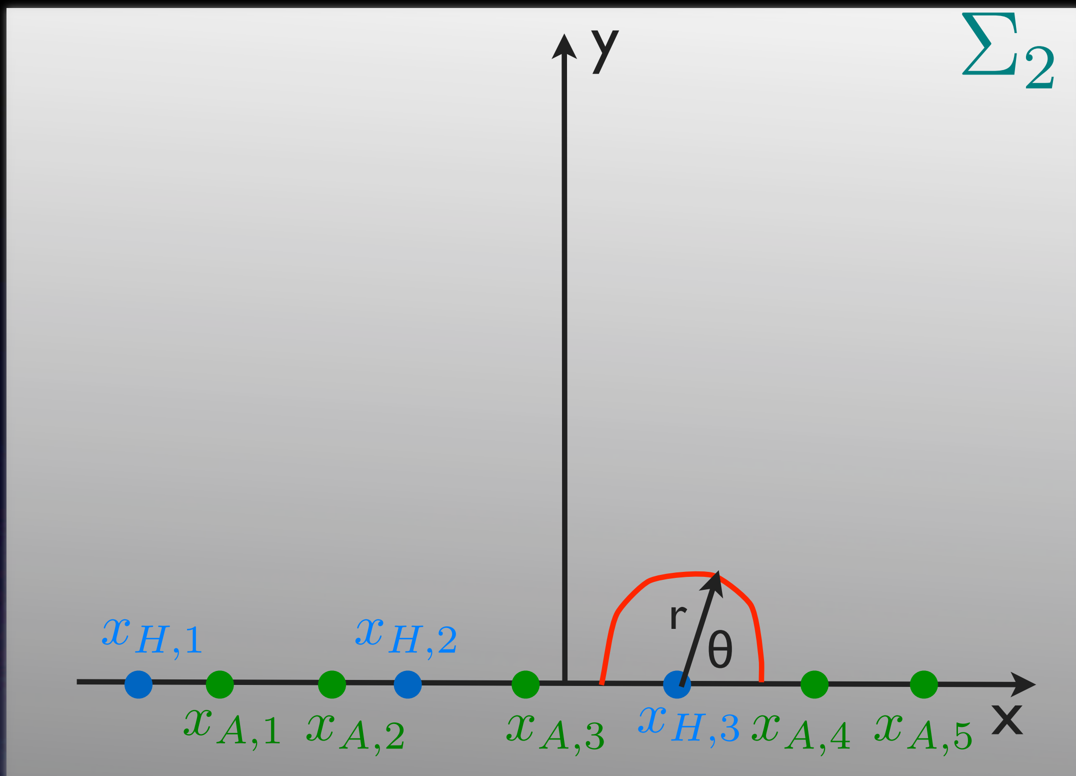
$K(x,y) = \mathcal{K}(z) + \mathcal{K}(\bar z)$ is determined by H,A,B.

Dual harmonic function $\tilde K(x,y) = i(\mathcal{K}(z) - \mathcal{K}(\bar z))$ contains one extra constant



number of moduli:
n-3 + n + 2n-2 +2n-2+1+1+1=6n-4

Holographic interface solutions



Expansion near pole of H

$$z - x_{H,i} = re^{i\theta}$$

$r \to 0$ gives asymptotic boundary region

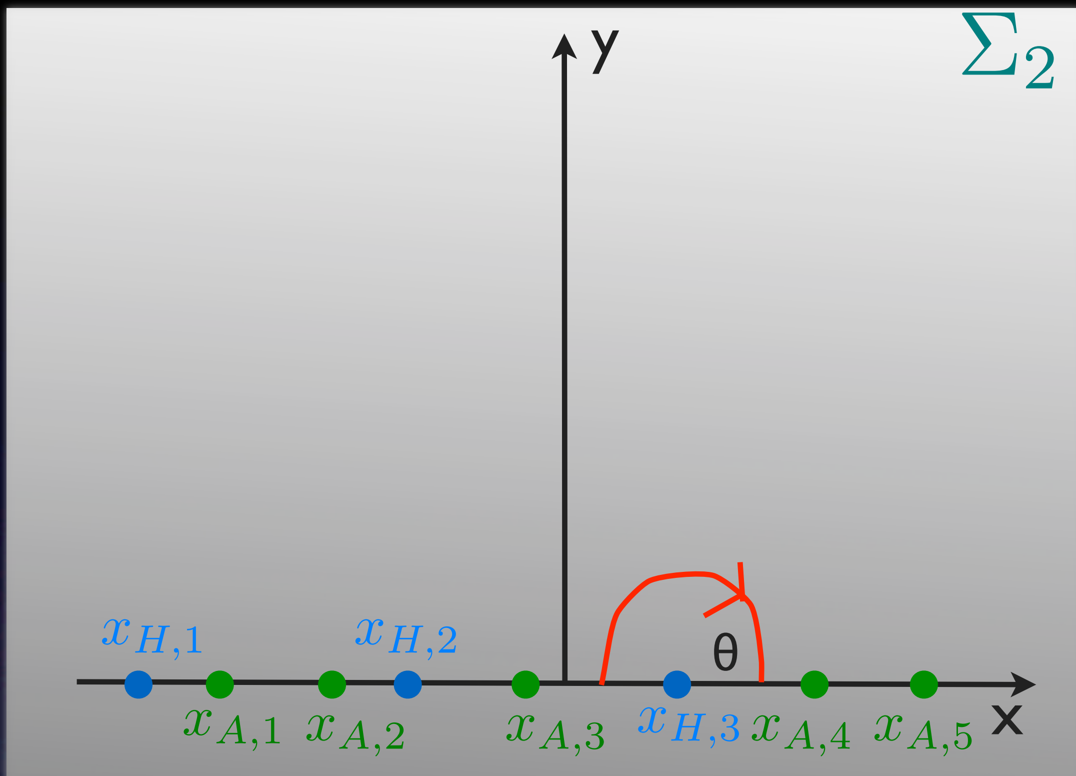
n = number of poles of H
= number of asymptotic AdS regions

$$ds^2 \to R^2_{AdS_{(i)}} \Big(\frac{1}{r^2} (dr^2 + ds^2_{AdS_2}) + d\theta^2 + \sin^2\theta ds^2_{S_2} \Big) + o(r^2)$$

Exponential map $r = e^{-x}$ produces Janus asymptotics

$$ds^2 \to R^2_{AdS_{(i)}} \Big(dx^2 + e^{2x} \frac{d\xi^2 - dt^2}{\xi^2} + ds^2_{S_3} \Big) + o(e^{-2x})$$

Holographic interface solutions



Expansion near pole of H

$$z - x_{H,i} = re^{i\theta}$$

As $r \to 0$ two sphere and θ make three spheres in the asymptotic region

$$ds^2 \to \cdots R^2_{AdS}(d\theta^2 + \sin\theta^2 ds^2_{S_2}) + \cdots$$

three spheres carry four charges: D1, D5, NS5 and F1. 4 (n-1) independent Page-charges

$$Q^{Page}_{NS5} = \int_{M_3} H_3, \qquad Q^{Page}_{D5} \int_{S_3} \left(\tilde{F}_3 + \chi H_3\right)$$

$$Q^{Page}_{D1} = -\int_{S_3 \times K_3} \left(e^{\phi} * \tilde{F}_3 - 4C_4 \wedge H_3\right)$$

$$Q^{Page}_{F1} = -\int_{S_3 \times K_3} \left(e^{-\phi} * H_3 - \chi e^{\phi} * \tilde{F}_3 + 4C_4 \wedge dC_2\right)$$

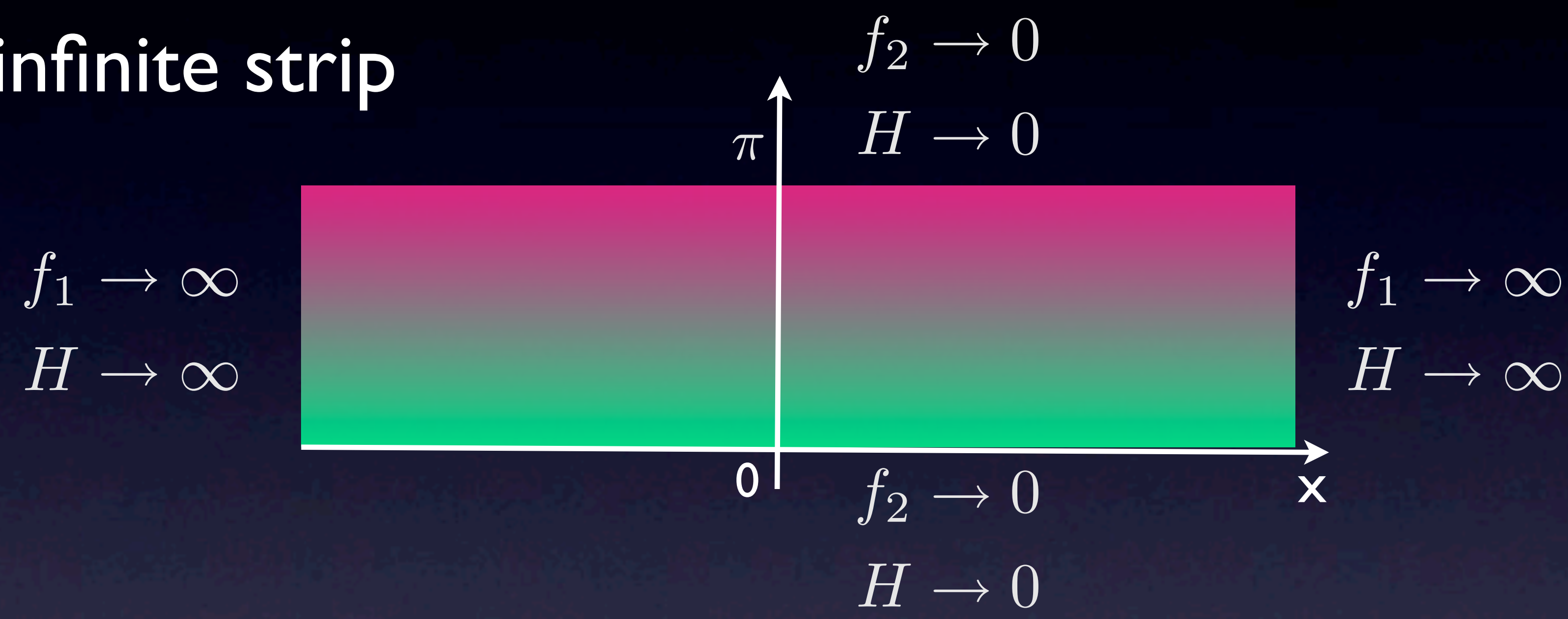
Half BPS Janus solutions

Simplest case: n=2, i.e. two poles of H and two asymptotic AdS regions.

Simple deformation of $AdS_3 \times S^3$ with RR flux

Exponential map takes Σ to infinite strip

$$\begin{aligned} w &= x + iy, \\ x &\in [-\infty, \infty] \\ y &\in [0, \pi] \end{aligned}$$



$$\begin{aligned} H &= -iL\sinh(w+\psi) + c.c. \\ A &= ik^2 \frac{\cosh\theta + \sinh\theta\cosh w}{\sinh w} + ib \\ B &= ik \frac{\cosh(w+\psi)}{\cosh\psi \sinh w} \\ K &= i\frac{\cosh\theta - \sinh\theta\cosh w}{\sinh w} + c.c. \end{aligned}$$

k, b SL(2,R) transformations

L size of AdS

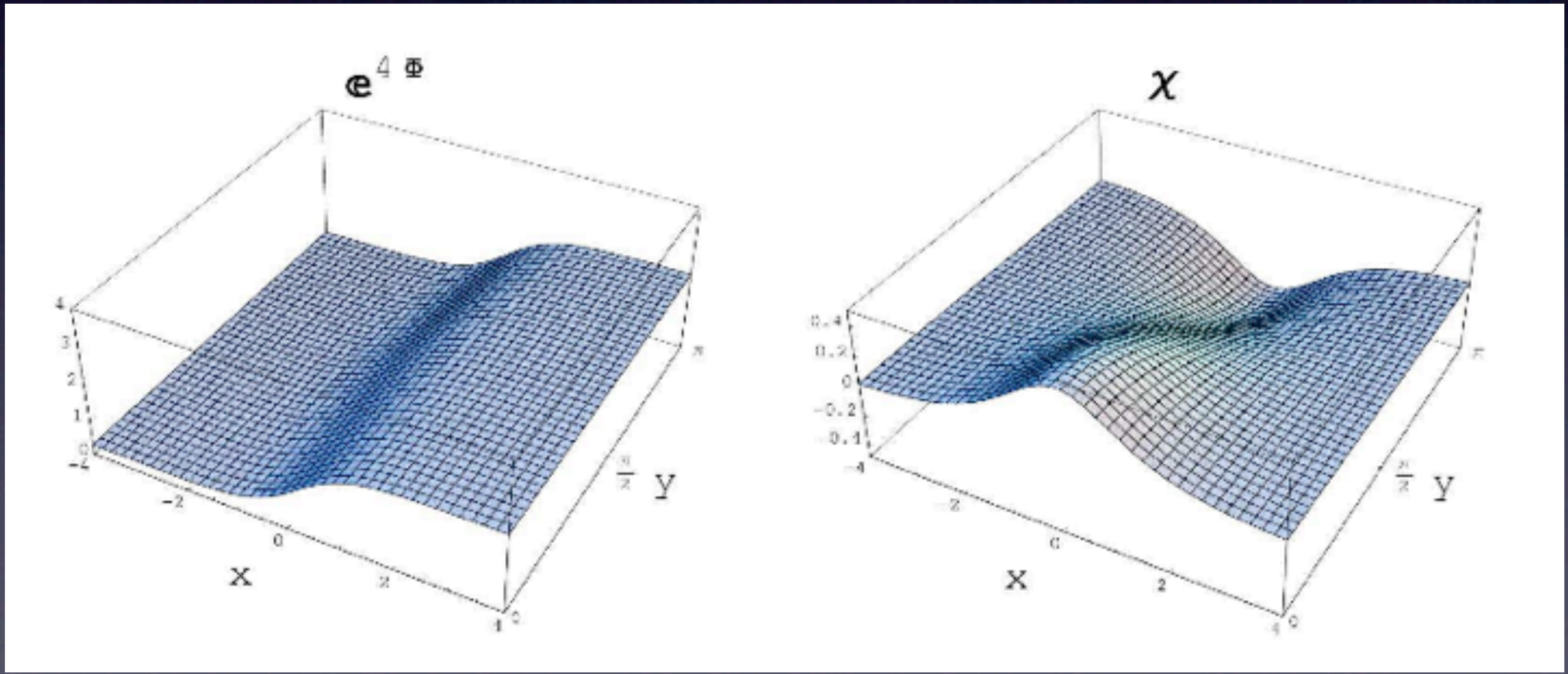
θ, ψ deformation parameter

Half BPS Janus solutions

axion and dilaton:

$$e^{4\Phi} = k^4 \frac{\cosh^2(x+\psi)\text{sech}^2\psi + \left(\cosh^2\theta - \text{sech}^2\psi\right)\sin^2 y}{\left(\cosh x - \cos y \tanh\theta\right)^2}$$

$$\chi = -\frac{k^2}{2}\frac{\sinh 2\theta \sinh x - 2\tanh\psi\cos y}{\cosh x\cosh\theta - \cos y\sinh\theta} - b$$



Plot for $\psi = \frac{1}{2}, \theta = 0, b = 0, k = 1 L = 1$ dilaton jumps !

Half BPS Janus solutions

axion and dilaton:

$$e^{4\Phi} = k^4 \frac{\cosh^2(x+\psi)\mathrm{sech}^2\psi + \left(\cosh^2\theta - \mathrm{sech}^2\psi\right)\sin^2 y}{\left(\cosh x - \cos y \tanh\theta\right)^2}$$

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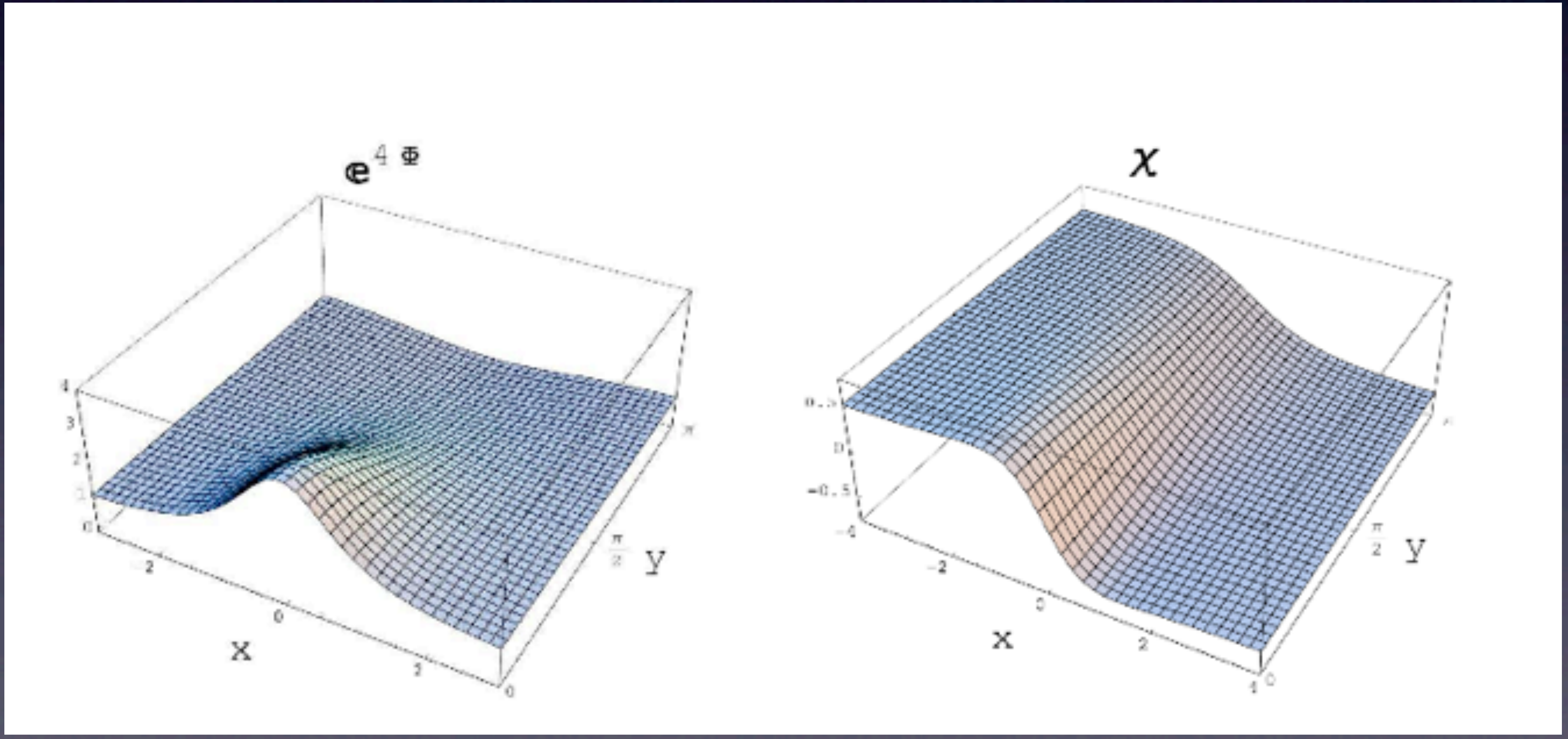


Plot for $\psi = 0, \theta = \frac{1}{2}, b = 0, k = 1, L = 1$ axion jumps !

Half BPS Janus solutions

holographic interpretation: Two combinations of massless scalars

$$e^{-2\Phi} f_3^4 \qquad \text{and} \qquad \chi - k^2 C_K$$

coupling constant of 2d CFT (α')
dual to $\Delta = 2$ operator O_0

blowup mode of orbifold
dual to $\Delta = 2$ operator T_0

Take different values in the two asymptotic regions

$$\begin{aligned} \phi &= \phi_-^0 + \phi_-^1(y)e^{x} + \dots \qquad \text{for } x \to -\infty \\ \phi &= \phi_+^0 + \phi_+^1(y)e^{-x} + \dots \qquad \text{for } x \to \infty \end{aligned}$$

In the dual 2dim CFT, the operators are added which jump across a 1dim interface:

$$\mathcal{L}_1 = \mathcal{L}_0 + \Theta(x^\perp)c_1 O_0 + \Theta(x^\perp)c_2 T_0$$

Half BPS Janus solutions

What are the operators O_0 and T_0 ? N=(4,4) SCFT. For simplicity consider $(T^4)^n/S_n$ orbifold

1. $$S = \frac{1}{4\pi}\int d^2z \sum_{i,a}\Big(\partial X_{i,a}\bar\partial X_{i,a} + \psi_{i,a}\bar\partial\psi_{i,a} + \bar\psi_{i,a}\partial\bar\psi_{i,a}\Big)$$

O_0 $(h,\bar h) = (1,1)$ descendant of $\sum_a \psi^i_a \bar\psi^j_a$ $(h,\bar h) = (1/2, 1/2)$

$$\mathcal{O}_0 = \sum_{i,a} \partial X_{i,a}\bar\partial X_{i,a} + \text{fermions}$$ ⇒ Jump in coupling constant

2. T_0 $(h,\bar h) = (1,1)$ operator with vanishing SU(2)xSU(2) R-symmetry descendant of Z_2 twist field

$$\lim_{z\to w}\,(G^2(z)\tilde G^{1\dagger}(\bar z) - G^{1\dagger}(z)\tilde G^{2\dagger}(\bar z))\Sigma^{\frac12,\frac12}(w,\bar w) = \frac{1}{(z-w)(\bar z-\bar w)}T^0(w,\bar w) + \cdots$$

⇒ Z_2 twist field jump: deformation away from orbifold point

Calculation of Boundary entropy

Divide system into subsystem A and complement B

$S_A = -tr_{H_A} \rho_A \log \rho_A . \qquad \rho_A = tr_{H_B} \rho$ is the entanglement entropy

The entanglement entropy for a system with an interface

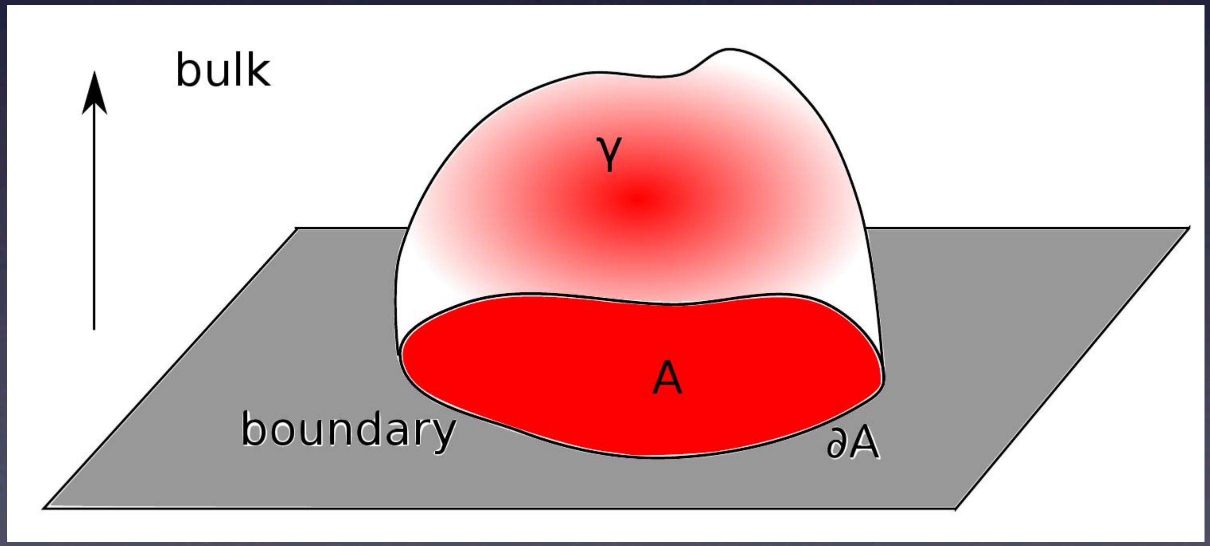
$$S_A = \frac{c}{6} \log \frac{L}{\epsilon} + \log g$$

where g is the g-function, i.e. boundary entropy of folded theory

Cardy and Calabrese

holographic calculation of entanglement entropy in AdS/CFT

Minimal surface γ in bulk ending on the boundary ∂A enclosing A



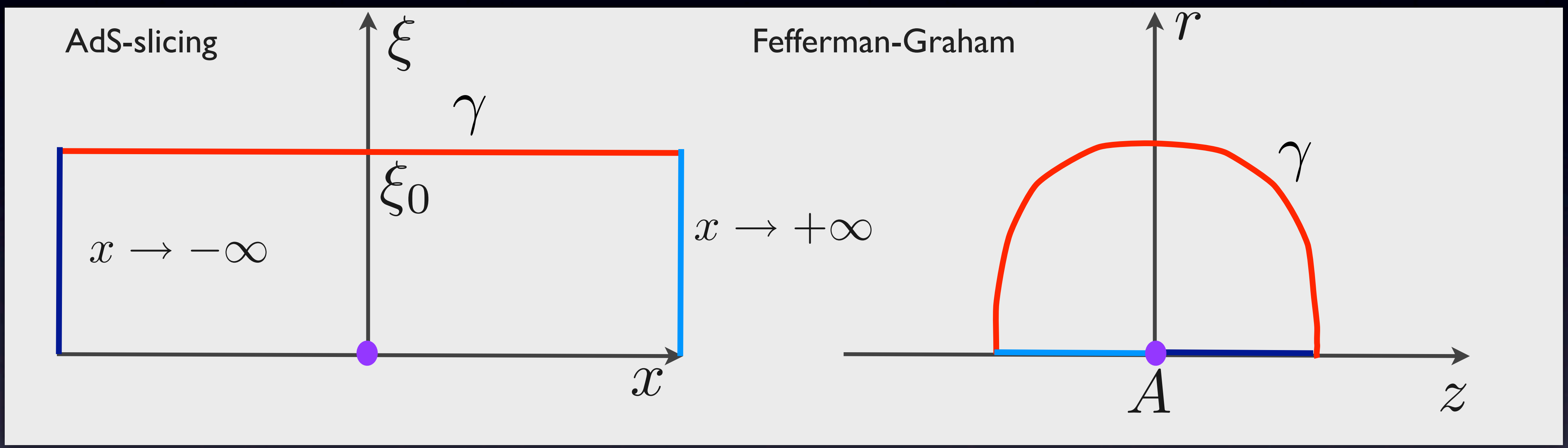
entanglement entropy: $$S_A = \frac{\text{Area}(\gamma)}{G_N^{d+1}}$$

Ryu and Takayanagi

Calculation of Boundary entropy

Minimal (static) surface for nonsupersymmetric Janus

$$ds_3^2 = dx^2 + f(x)\frac{d\xi^2 - dt^2}{\xi^2}$$



UV-divergence as $|x| \to \infty$ is regulated by cutoff.

For BPS-Janus solution: trace over all states with R-charges in entropy is equivalent to integration over three sphere

Calculation of Boundary entropy

For BPS Janus: minimal surface γ spans Σ, two sphere at $z = z_0$ in AdS_2

$$A(\theta,\psi) = \int d\Omega_2 \int dx \int dy \, (f_2^2 f_3^2) \times (\rho^2 f_3^2) = V_{S^2} \int dxdy \frac{H^2 \rho^2}{f_1^2}$$

A is divergent as x $\rightarrow \infty$, and has to be regularized using a UV cutoff

The boundary entropy is given by the difference of A and the area of the minimal surface in pure AdS with the same radius

AdS: $$S_{bd} = \frac{A(\theta,\psi) - A_0}{4G_N} = \frac{2c}{3} \ln \sqrt{\cosh\theta \cosh\psi}$$

Calculation of Boundary entropy

For BPS Janus: minimal surface γ spans Σ, two sphere at $z = z_0$ in AdS_2

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A is divergent as x $\rightarrow \infty$, and has to be regularized using a UV cutoff
The boundary entropy is given by the difference of A and the area of the minimal surface in pure AdS with the same radius

AdS: $$\theta = 0 \rightarrow S_{bd} = \frac{A(\theta,\psi) - A_0}{4G_N} = \frac{2c}{3} \ln \sqrt{\cosh \psi}$$

For $\theta = 0$ (pure radius deformation) one can compare this to the boundary entropy for n=2/3c bosons where radius jumps from r_+ to r_-

CFT: $$S_{bd} = \frac{2}{3} c \ln \sqrt{\frac{1}{2}\left(\frac{r_+}{r_-} + \frac{r_-}{r_+}\right)} = \frac{2}{3} c \ln \sqrt{\cosh \psi}$$

where $$\frac{r_+}{r_-} = e^{\psi}$$

Complete agreement ! Not true for non BPS Janus solution

T.Azeyanagi, A.Karch, T.Takayanagi and E.G.Thompson

Calculation of Boundary entropy

For BPS Janus: minimal surface γ spans Σ, two sphere at $z = z_0$ in AdS_2

$$A(\theta,\psi) = \int d\Omega_2 \int dx \int dy \, (f_2^2 f_3^2) \times (\rho^2 f_3^2) = V_{S^2} \int dx dy \frac{H^2 \rho^2}{f_1^2}$$

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The boundary entropy is given by the difference of A and the area of the minimal surface in pure AdS with the same radius

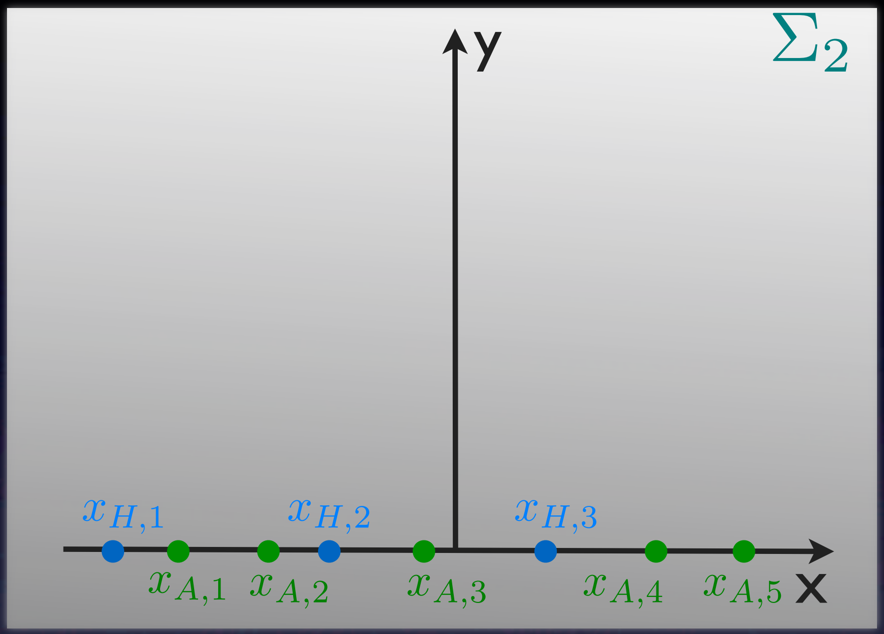
AdS: $$S_{bd} = \frac{A(\theta,\psi) - A_0}{4G_N} = \frac{2c}{3} \ln \sqrt{\cosh\theta \cosh\psi}$$

Prediction for boundary entropy for both radius mode jumps by $\mathcal{O}_0$ and orbifold blowup mode jumps by T_0

This has not calculated been calculated in the CFT ! Some evidence from conformal perturbation theory.

Multi Janus solutions

What is the holographic interpretation of the solutions with n>2 ?



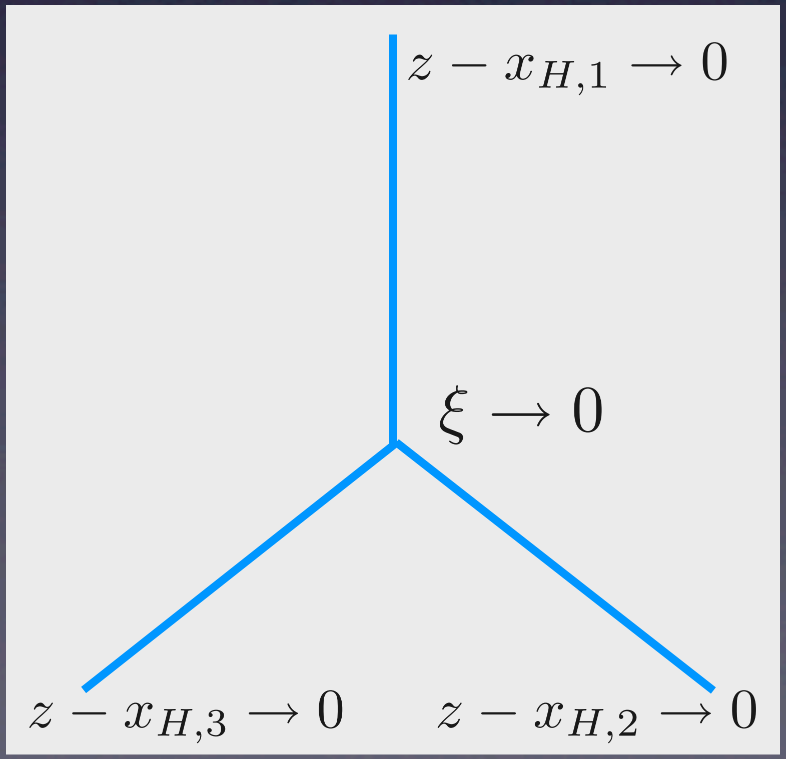
$$ds^2 \quad \rightarrow \quad \frac{1}{r^2}\left(dr^2 + \frac{d\xi^2 - dt^2}{\xi^2}\right) ds^2_{S_3}$$
$$= \frac{1}{r^2\xi^2}\left(\xi^2 dr^2 + d\xi^2 - dt^2\right) + \xi^2 ds^2_{S_3}$$

$$z - x_{H,i} = re^{i\theta} \qquad r \rightarrow 0$$

n asymptotic AdS regions : n half lines ξ>0

glued together at a point $\xi = 0$

A junction (star graph) of n CFTs defined half spaces



Multi Janus solutions

What are the CFT's ? Counting of 6n-4moduli of BPS interface solution

n 3-spheres: support D1,D5, NS5 and F1 charges: 4(n-1)

Attractor mechanism: in each asymptotic region 2 scalars are fixed

$$\begin{aligned} 4C_K \frac{e^{-\phi}}{f_3^4} + \chi &= -\frac{Q_{F1}}{Q_{D1}} + (f_3^8 + 16C_K^2)\frac{e^{-\phi}}{f_3^4}\frac{Q_{NS5}}{Q_{D1}} \\ \frac{e^{-\phi}}{f_3^4} &= \frac{Q_{D5}}{Q_{D1}} + (4C_K\frac{e^{-\phi}}{f_3^4} - \chi)\frac{Q_{NS5}}{Q_{D1}} \end{aligned}$$

2 scalars are free: 2n parameters

$\Rightarrow$ 6n-4 parameters corresponding to 6n-4 moduli of BPS interface solution

Junctions of n arbitrary (U-duals) of D1/D5 CFT with radius and orbifold deformations

Multi Janus solutions

Are these solutions related to configurations of branes in flat space ?

Bound state of D5 and NS5 branes wrapped on K3 and D1 and F1 in six dimensions all preserve 1/2 Susy of six dim Sugra and are selfdual strings

$$\{Q^a_\alpha, Q^b_\beta\} = (P_+ C_{(6)} \gamma^\mu_{(6)})_{\alpha\beta} \Big(C^{ab}_{(4)} P_\mu + (C_{(4)}\Gamma_i)^{ab} Z^i_\mu \Big)$$

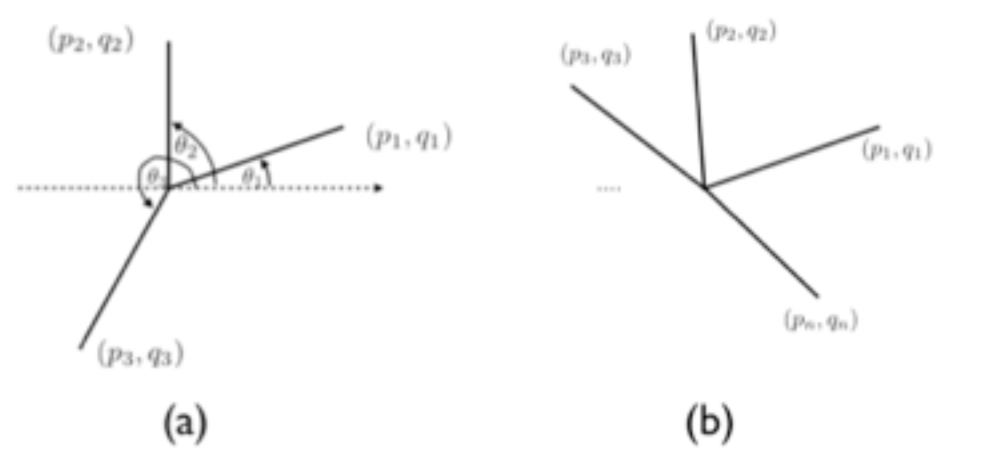


Figure 2: (a) Three string junction (b) multi-string junction

Just as in Sen's string network: junction of 1/2 BPS strings in six dimensions preserves 1/4 of susy if strings intersect in a plane and angles are correlated with the charges

Near horizon limit: enhancement of supersymmetry and coformal symmetry

Conclusions

- Exact half BPS solutions which are locally asymptotic to $AdS_3 \times S^3 \times K_3$
- n=2 solution supersymmetric Janus solution
- n>2 solution dual to junctions of n 1+1 dim CFT's
- Solution has 6n-4 moduli identified with physical parameters of the CFT (Brane charges and expectation values of marginal operators)
- Calculation of boundary entropy for radius jump for supersymmetric Janus solution gives excat agreement with BCFT calculation

Conclusions

Work in progress

- Calculation of reflection on transmission matrices for junctions using holographically
- Calculation of boundary entropy for the junction
- Comparison to CFT for junctions with radius jumps
- Applications of holographic dual to junctions of quantum wires
- In the solutions presented one did not turn on moduli of K3 and fluxes on two cycles of K3: generalize to solutions of N=4b 6dim supergravity