Symmetries of $T\bar{T}$ – deformed CFTs and their holographic avatars

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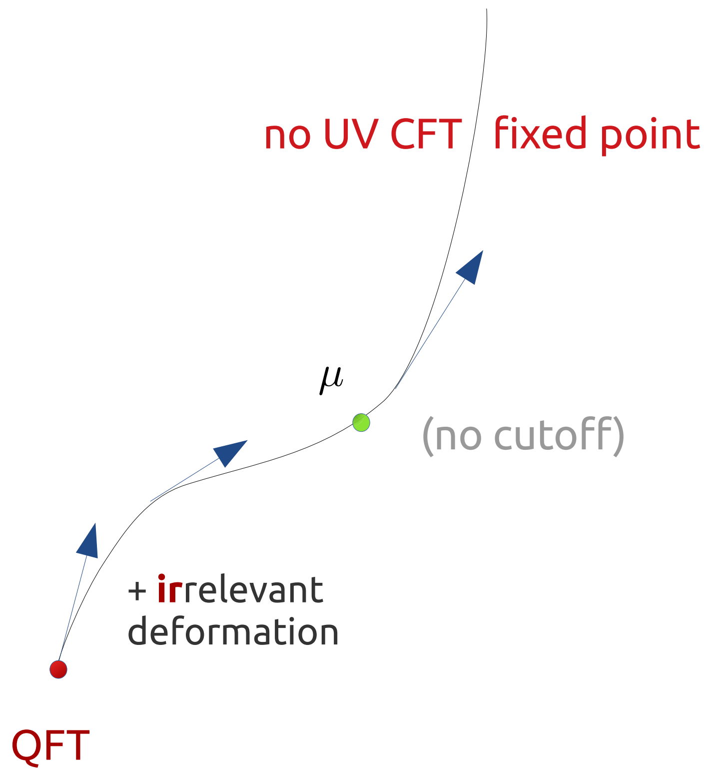
based on 2212.09768 with Silvia Georgescu

What is the $T\bar{T}$ deformation?

- irrelevant deformation of 2d QFTs → UV complete QFTs that are non-local



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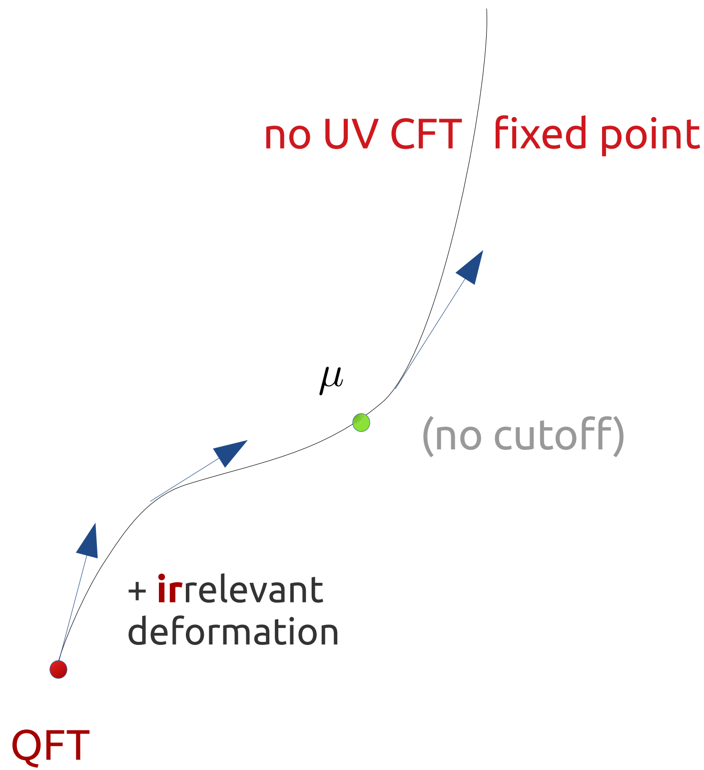
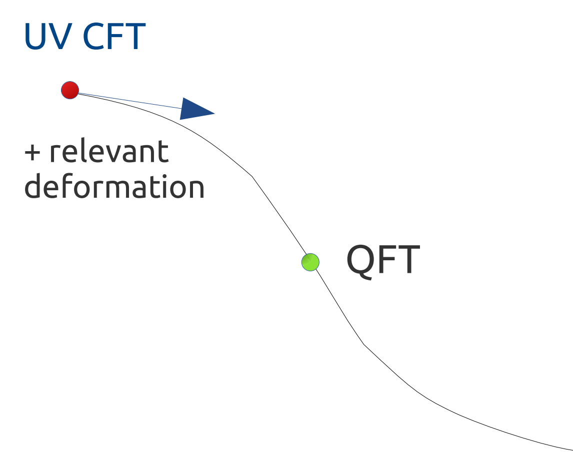


- finely tuned irrelevant flow

  integrability preserved

- well-defined S-matrix → UV completeness

- not an RG flow



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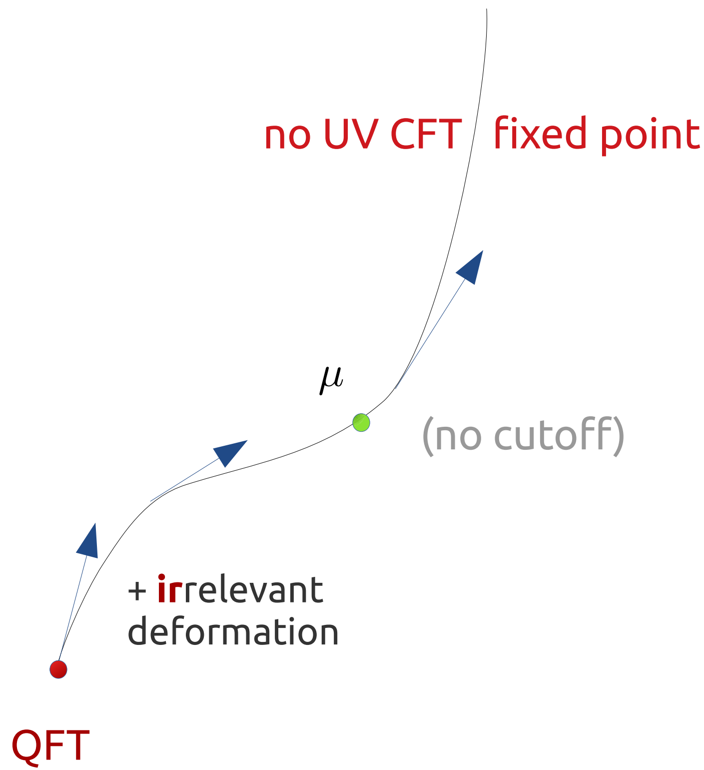
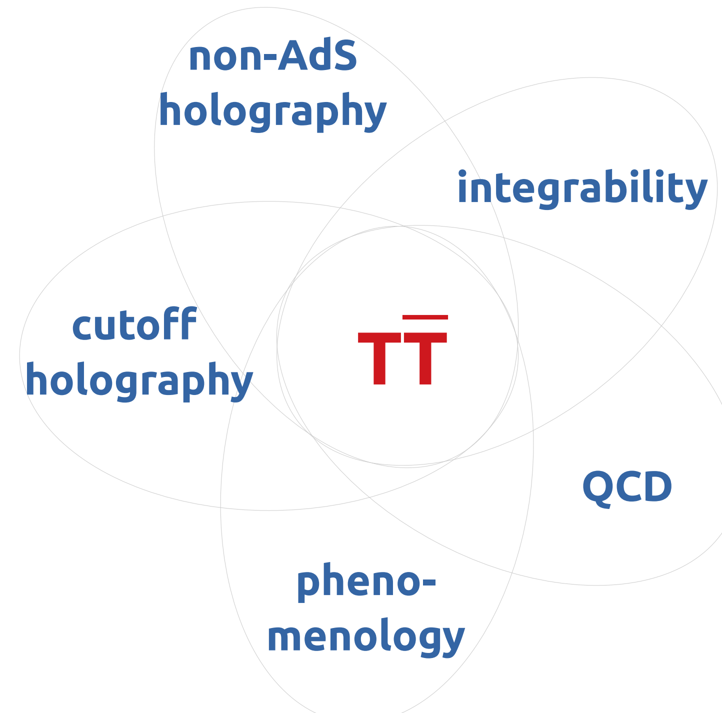
- irrelevant deformations of 2d QFTs → UV complete QFTs that are non-local





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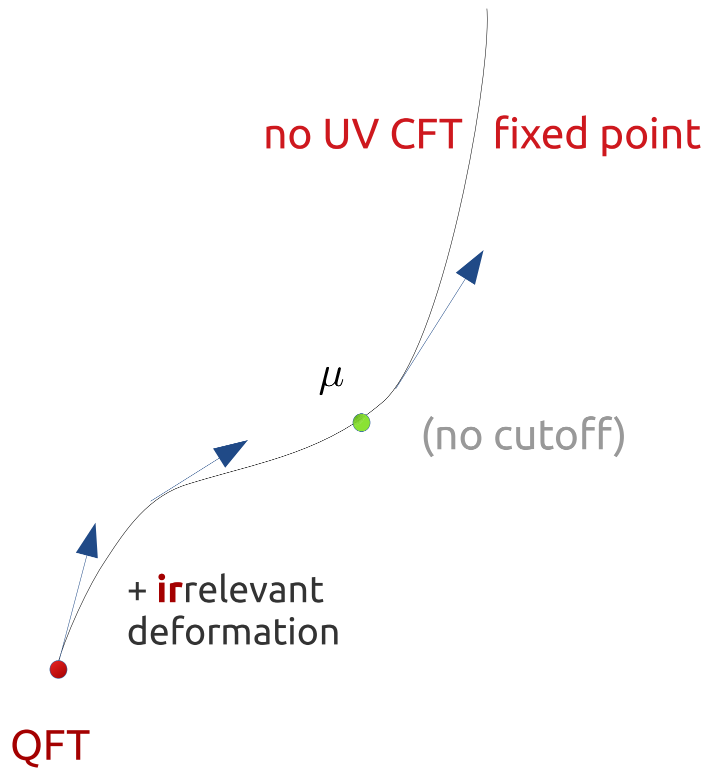
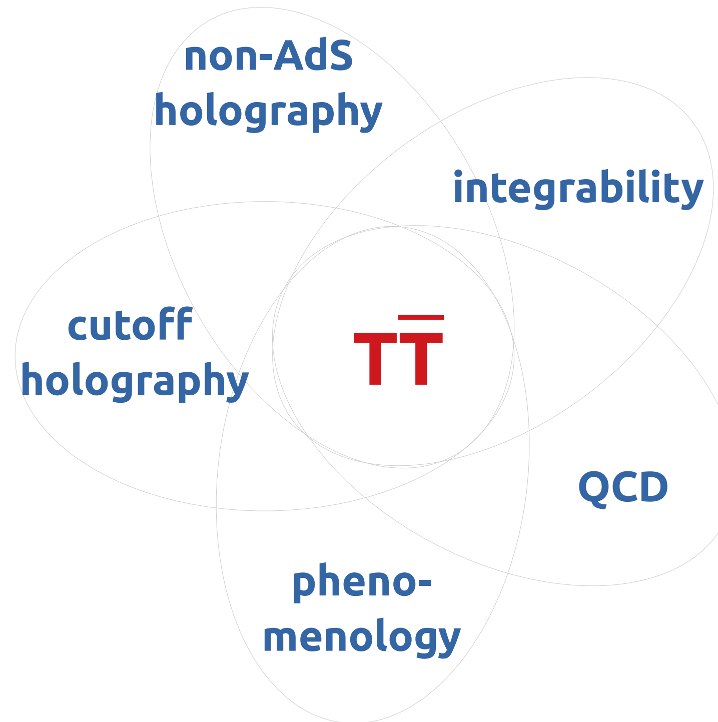




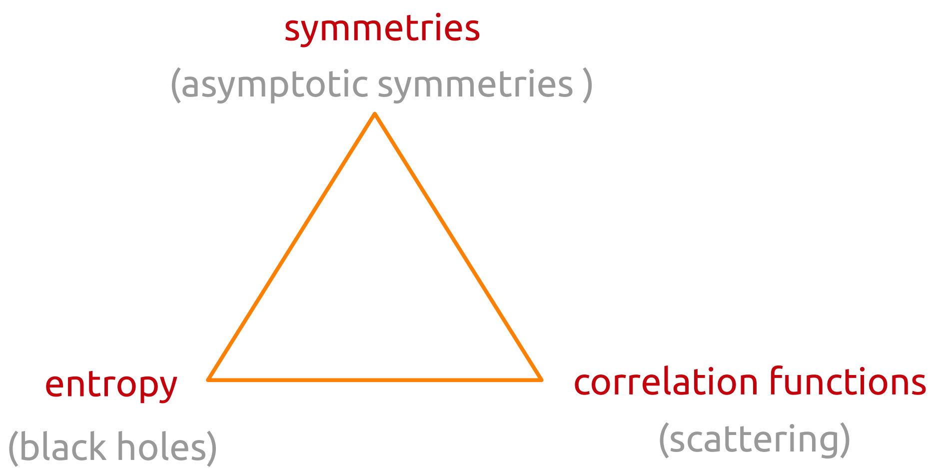
exactly solvable

Motivation from non-AdS holography

- non-AdS holography : **hard** → no concrete examples in string theory for asympt. flat, de Sitter, etc.

- infer properties of dual QFT from spacetime: symmetries, thermodynamics, correlation functions

e.g. celestial holography programme



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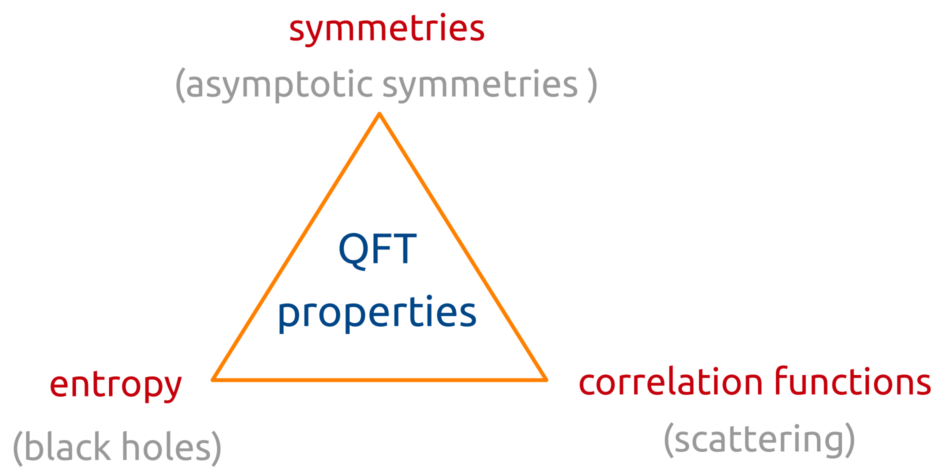

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- valuable to have an independent QFT definition of the dual field theory

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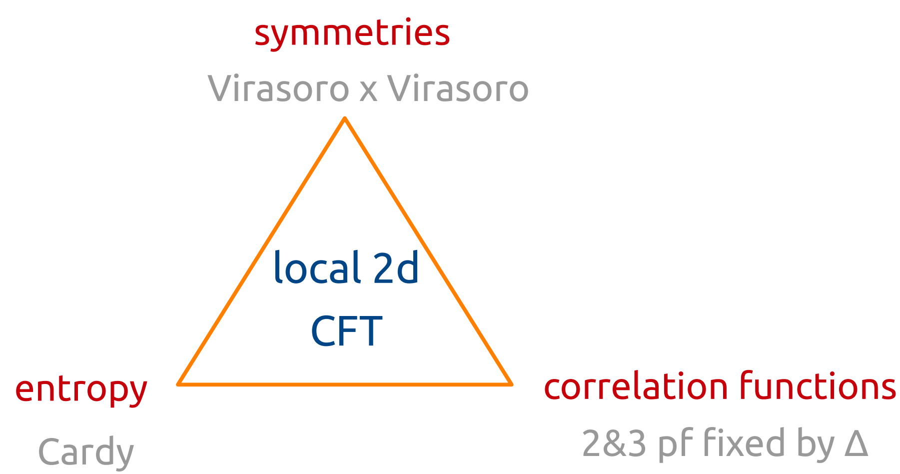

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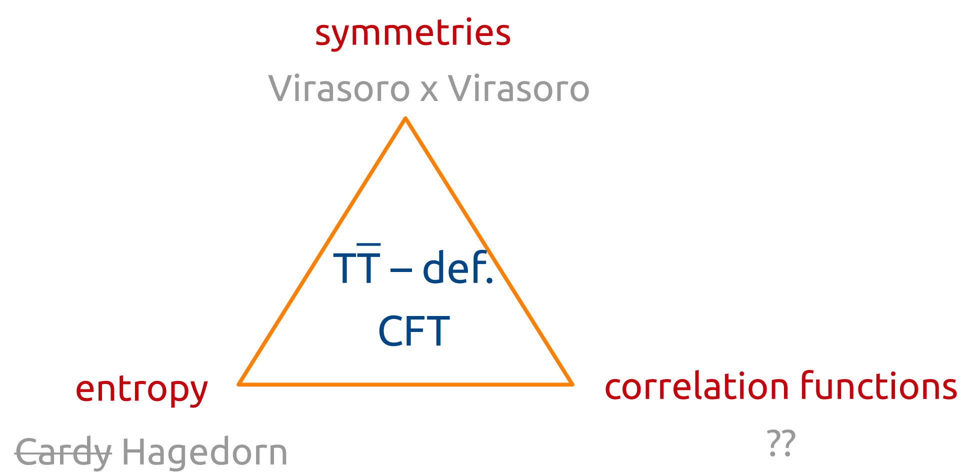

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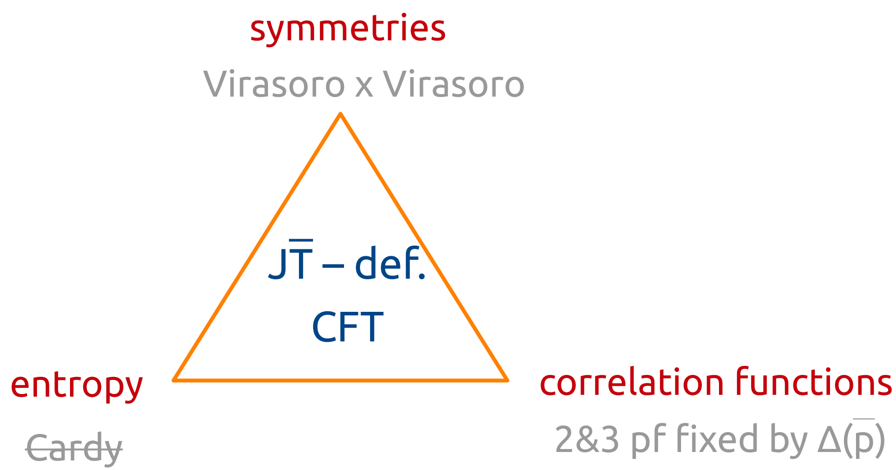

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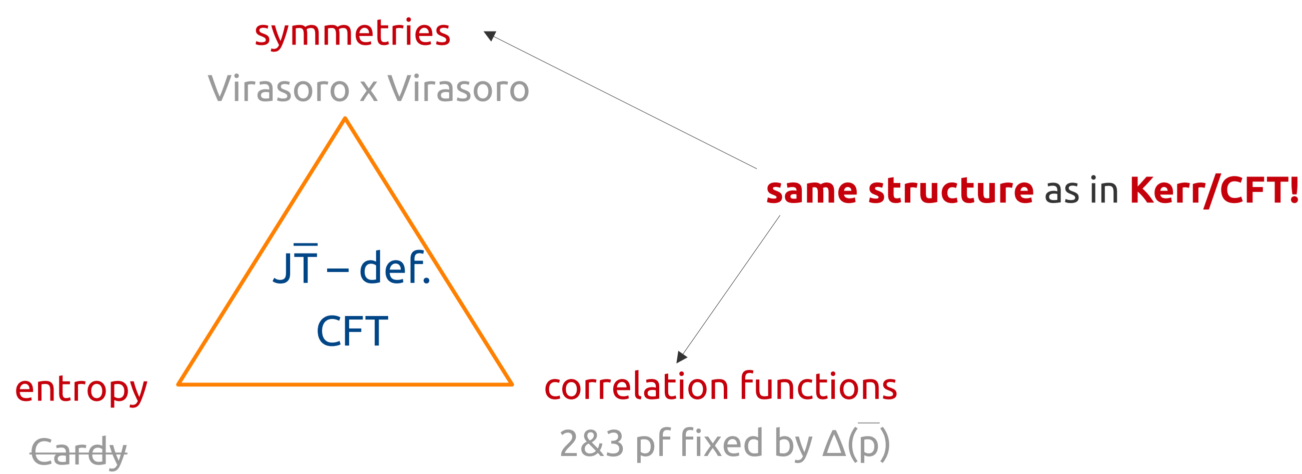

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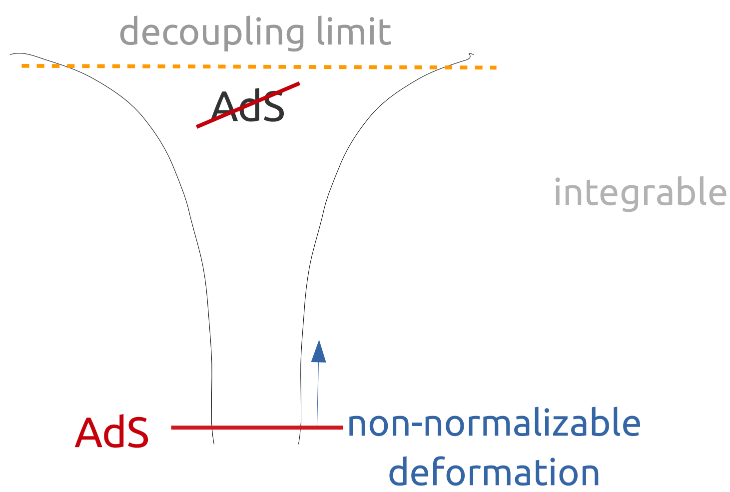
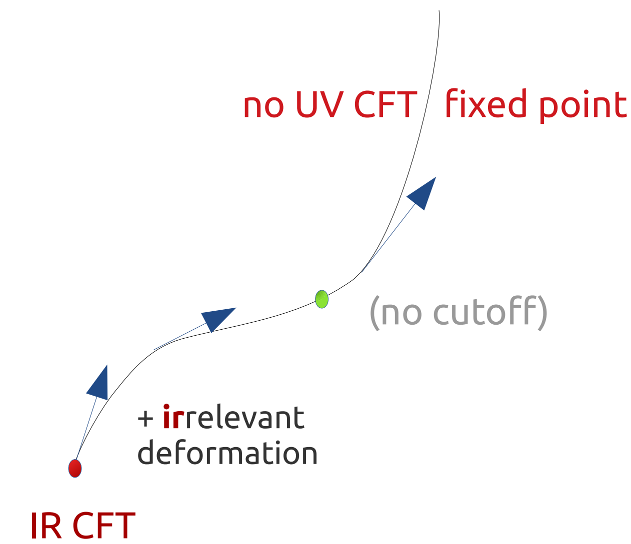
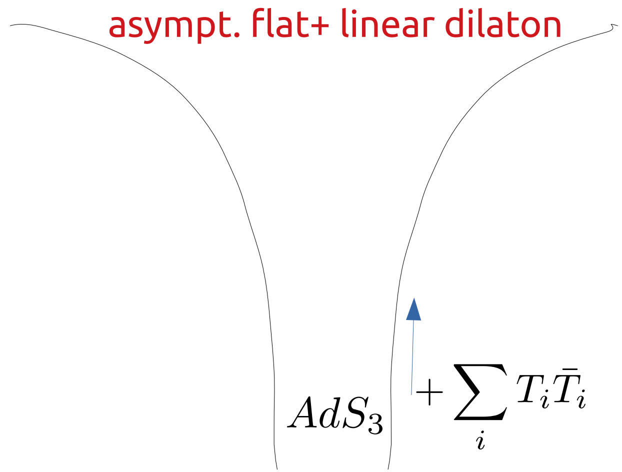




- define holographic dual in terms of finely-tuned irrelevant flow → (non-local) QFT
- understood in rare examples: non-commutative N=4 SYM, dipole-deformed N=4 SYM
- generically strongly-coupled & **very** hard to follow

Main result

Giveon, Itzhaki, Kutasov '17



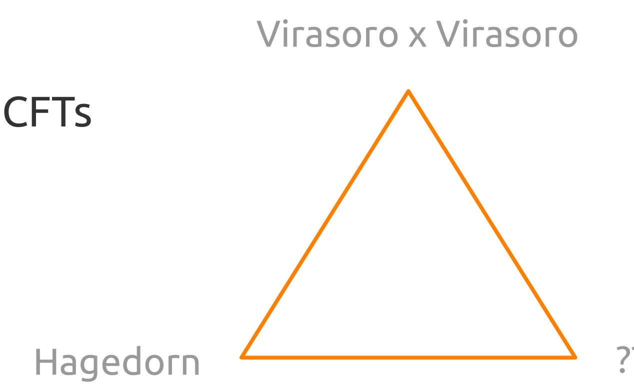
= ``single-trace'' $T\bar{T}$ – deformed CFT

conjectured

has precisely the infinite symmetries of (single-trace) $T\bar{T}$ – deformed CFTs

→ perhaps the "QFT structure" that is relevant to this spacetime

is that of $T\bar{T}$ – deformed CFTs



Plan

- brief review of $T\bar{T}$ deformations

- brief review of the holographic interpretation:

  - of the standard "double-trace" deformation → AdS_3 with mixed bnd. cond. for the metric

  - of the "single-trace" variant → asymptotically flat with a linear dilaton

- infinite symmetries of $T\bar{T}$ – deformed CFTs as asymptotic symmetries of the AdS_3 with mixed b.c.

- asymptotic symmetry group analysis of the asymptotically linear dilaton backgrounds

- conclusions

The $T\bar{T}$ deformation

- **universal** irrelevant deformation of 2d QFTs → bilinear in the stress tensor components

- define $T\bar{T}$ operator

$$\lim_{y \to x} \varepsilon^{\alpha\beta} \varepsilon^{AB} T_{\alpha A}(x) T_{\beta B}(y) = \mathcal{O}_{T\bar{T}}(x) \text{ +derivative terms}$$

Zamolodchikov '04

SZ '16

nice factorization properties

- the $T\bar{T}$ deformation :

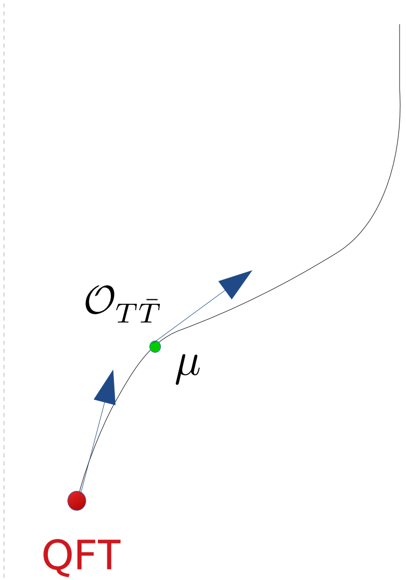
$$\frac{\partial S(\mu)}{\partial \mu} = \int d^2x \, \mathcal{O}_{T\bar{T}}(\mu) \qquad [\mu] = (length)^2$$

Smirnov & Zamolodchikov '16; Cavaglia et al. '16

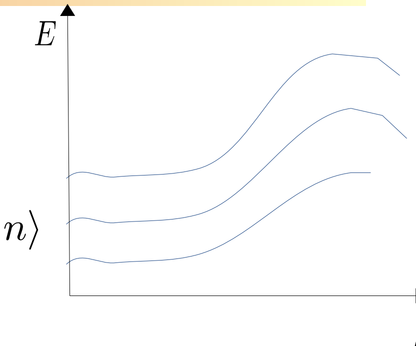
- highly tractable : exact finite -size spectrum, S-matrix, preserves integrability

- deformed theory non-local (scale $\sqrt{\mu}$) but argued UV complete

minimum length



$T\bar{T}$ - deformed CFT spectrum & thermodynamics



- in compact space (R) → energy levels continuously deformed

- deformed energies $E_\mu(R)$ determined only by initial spectrum $\partial_\mu E_n = \langle n|\mathcal{O}_{T\bar{T}}|n\rangle$

e.g. seed CFT

$$E_\mu(R) = \frac{R}{2\mu}\left(\sqrt{1+\frac{4\mu E_0}{R}+\frac{4\mu^2 P^2}{R^2}}-1\right)$$

R → 0 $\Rightarrow$ UV is not a CFT

$\mu > 0$: ground state energy $E_0 = -\frac{c}{12R}$ becomes complex for $R < R_{min} = \#\sqrt{\mu c}$

$\mu < 0$: all states with $E_0 > \frac{R}{4|\mu|}$ acquire imaginary energies → no sense in compact space (CTC)

Cooper, Dubovsky, Moshen

- thermodynamics: smoothly deformed levels → unchanged density of states

$$S(E) = S_{Cardy}(E^{(0)}(E)) = \sqrt{\frac{2\pi c}{3}(ER+\mu E^2)} \qquad (P=0)$$

- Hagedorn behaviour $S \propto E$ at high energy $T_H = R_{min}^{-1}$

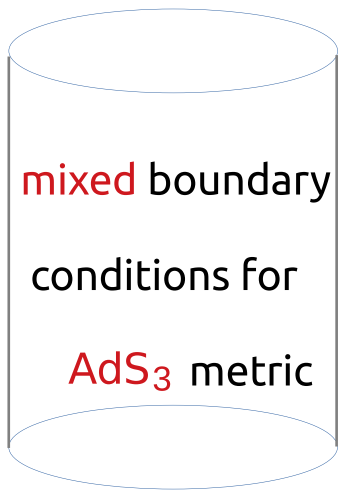
Holographic interpretation of $T\bar{T}$ – deformed CFTs

Holographic dual of $T\bar{T}$ - deformed CFTs

- $T\bar{T}$ deformation : **double trace**

- seed CFT : large c, large gap

  → Einstein gravity + low-lying matter fields



$$g^{(0)}_{\alpha\beta} - \mu g^{(2)}_{\alpha\beta} + \frac{\mu^2}{4} g^{(2)}_{\alpha\gamma} g^{(0)\gamma\delta} g^{(2)}_{\delta\beta}$$

fixed

- holographic dictionary derived from field theory using Hubbard-Stratonovich trick

- 1st instance of mixed bnd. cond. on AdS_3 metric

  → bulk & boundary have independent definitions

  → contrast standard situation where properties of the boundary theory are inferred from the bulk

- change bnd. conditions on AdS_3 metric → radical modification of the bnd. theory: local → non-local

- precision holography

  → perfect match of bulk/boundary spectrum ✓

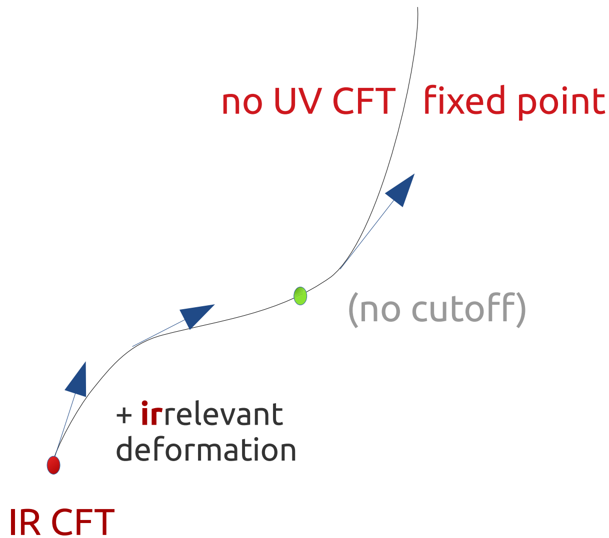
  → symmetries ✓

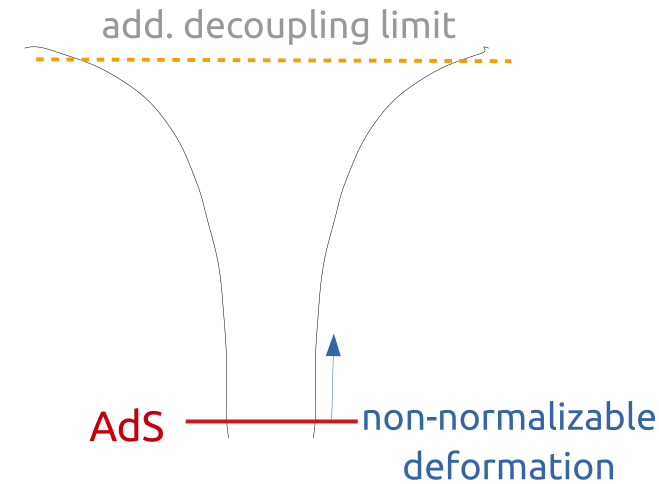
  → other observables?

MG, Monten '19

$T\bar{T}$ & non-AdS holography

The "single-trace" $T\bar{T}$ deformation





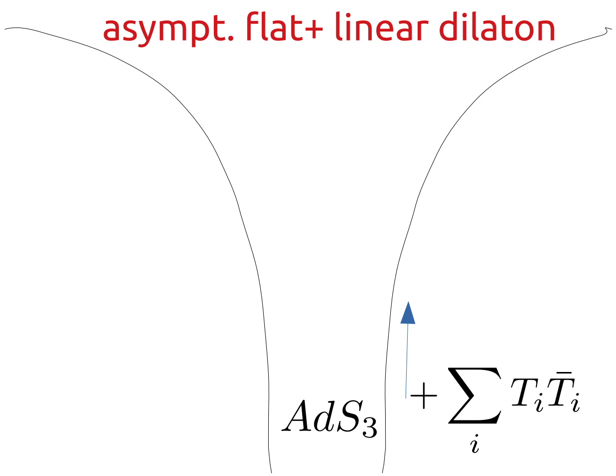
- $T\bar{T}$ ↛ non-AdS geometry because it is double-trace → need single-trace irrelevant deformation
- AdS_3/CFT_2 gauge group: S_p (permutations)

Giveon, Itzhaki, Kutasov '17

seed symmetric product orbifold CFT ⟺ "single-trace $T\bar{T}$" deformation (finite μ)

$$\mathcal{M}^p/S_p \qquad\qquad \sum_{i=1}^{p} T_i\bar{T}_i \quad \Rightarrow \quad (T\bar{T}_{def.}\,\mathcal{M})^p/S_p$$

The asymptotic linear dilaton background and $T\bar{T}$



N_5 NS5 and N_1 F1 strings in the NS5 decoupling limit

$g_s \to 0\,, \quad \alpha'$ fixed

N_1 large

UV: Little String Theory

non-gravitational, non-local theory with Hagedorn growth

IR: AdS_3 ~ descr. by $(\mathcal{M}_{6N_5})^{N_1}/S_{N_1}$ symmetric orbifold CFT

- worldsheet σ - model : exactly marginal deformation of the WZW model describing AdS_3 by $J^-\bar{J}^-$

  → dual to CFT source for a $(2,2)$ single-trace operator $\sum_{i=1}^{N_1} T_i\bar{T}_i$

- proposed holographic relation

$$Z_{string}[\text{NS5- F1}] = Z\left[(T\bar{T} - \text{def. CFT}_{6N_5})^{N_1}/S_{N_1}\right] \qquad \mu = \pi\alpha'$$

Giveon, Itzhaki, Kutasov '17

Checks of the correspondence

$$\mathcal{Z}_{string\ theory}[\text{NS5- F1}] = \mathcal{Z}\left[(T\bar{T}\text{- deformed}\,\mathcal{M}_{6N_5})^{N_1}/S_{N_1}\right]$$

solvable QFT!

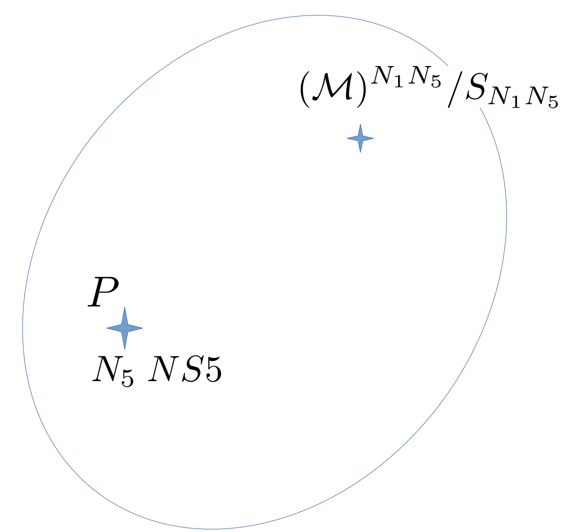
- both sides (independently) well-defined at finite deformation ✓

- spectrum of long string excitations exactly matches single-trace $T\bar{T}$ spectrum GIK '17

- black hole entropy $S(E)$ agrees with $T\bar{T}$ entropy (Cardy → Hagedorn) GIK '17

- **!** full CFT dual to AdS_3 is not a symmetric product orbifold

- our perfect match of the (infinite) symmetries brings further support for the GIK proposal



Infinite symmetries of TT – deformed CFTs:

holographic analysis

Asymptotic symmetries

MG, Monten '19

- holographic dual to double-trace $T\bar{T}$ – deformed CFTs: AdS $_3$ with mixed bnd. cond.

$$g^{(0)}_{\alpha\beta} - \mu g^{(2)}_{\alpha\beta} + \frac{\mu^2}{4} g^{(2)}_{\alpha\gamma} g^{(0)\gamma\delta} g^{(2)}_{\delta\beta}$$

- large diffeomorphisms that preserve the mixed bnd. conditions symmetries of dual field theory

- fix $T\bar{T}$ metric to be flat → most general allowed backgrounds param. by two functions $\mathcal{L}(u), \bar{\mathcal{L}}(v)$

$$g^{(0)} : \underbrace{\frac{(dU + \mu\bar{\mathcal{L}}(v)dV)(dV + \mu\mathcal{L}(u)dU)}{(1-\mu^2\mathcal{L}(u)\bar{\mathcal{L}}(v))^2}}_{du dv} \qquad g^{(2)} : \frac{\left(1+\mu^2\mathcal{L}(u)\bar{\mathcal{L}}(v)\right)\left(\mathcal{L}(u)\, dU^2 + \bar{\mathcal{L}}(v)\, dV^2\right) + 4\mu\mathcal{L}(u)\bar{\mathcal{L}}(v)\, dU dV}{\left(1-\mu^2\mathcal{L}(u)\bar{\mathcal{L}}(v)\right)^2}$$

where the field-dependent coordinates u, v are defined as

$$\begin{cases} U = u - \mu \int^v \bar{\mathcal{L}}(v')\, dv' \\ V = v - \mu \int^u \mathcal{L}(u')\, du' \end{cases}$$

zero modes $c_{\mathcal{L}}, c_{\bar{\mathcal{L}}}$

- diffeomorphisms that preserve the mixed bnd. cond:

$$\xi^U = f(u) + \mu \underbrace{\int^v \bar{\mathcal{L}}\bar{f}'}_{c_{\mathcal{L}_f}} + \frac{\ell(\rho+\mu)(\rho\bar{\mathcal{L}}f''(u) - \bar{f}''(v))}{8\pi G(1-\rho^2\mathcal{L}\bar{\mathcal{L}})} \qquad \xi^V = \bar{f}(v) + \mu \underbrace{\int^u \mathcal{L}f'}_{c_{\bar{\mathcal{L}}_{\bar{f}}}} + \frac{\ell(\rho+\mu)(\rho\mathcal{L}\bar{f}''(v) - f''(u))}{8\pi G(1-\rho^2\mathcal{L}\bar{\mathcal{L}})}$$

- $T\bar{T}$ metric ~ induced metric at $\rho = -\mu$

$$\xi^\rho = \rho(f'(u) + \bar{f}'(v))$$

Constraints on the asymptotic functions

- under these diffeomorphisms, the T$\overline{\text{T}}$ coordinates change as

$$U \to U + f(u) + \mu \int^v \bar{\mathcal{L}} \bar{f}' \qquad\qquad V \to V + \bar{f}(v) + \mu \int^u \mathcal{L} f'$$

winding!

- the functions $f, \bar{f}$ must have winding, in order for the periodicity of the T$\overline{\text{T}}$ coordinates to not change

$$f(u) = f_p(u) + w_f u \;, \qquad \bar{f}(v) = \bar{f}_p(v) + w_{\bar{f}} v$$

- this winding is entirely fixed by the periodic part through the conserved charges of the background

$$2\pi w_f R_u + \mu \oint dv \bar{\mathcal{L}} \bar{f}_p'(v) + 2\mu w_{\bar{f}} H_R = 0 \;, \qquad 2\pi w_{\bar{f}} R_v + \mu \oint du \mathcal{L} f_p'(u) + 2\mu w_f H_L = 0$$

where $R_{u,v}$ are the field-dependent radii of u, v and $H_{L,R}$ are the left/right-moving energies

$$2\pi R_u = 2\pi R + 2\mu H_R \;, \qquad 2\pi R_v = 2\pi R + 2\mu H_L$$

Basics of the covariant phase space formalism

- this formalism computes the infinitesimal charge difference between two backgrounds

$$\not{\delta}\boldsymbol{Q}_\xi = \oint \boldsymbol{k}_\xi[\delta\Phi, \Phi]$$

where the d-2 form $\boldsymbol{k}_\xi$ is directly constructed form the action

- this charge needs to be integrable, checked separately $\leftarrow$ **essential**

- charge algebra

$$\{Q_\xi, Q_\chi\} \equiv \delta_\chi Q_\xi = \oint \boldsymbol{k}_\xi(\mathcal{L}_\chi\Phi, \Phi)$$

- based on the representation theorem $\delta_\chi Q_\xi = Q_{[\xi,\chi]_*}$

- the modified Lie bracket takes into account the possible field-dependence of the diffeomorphisms

Barnich, Toessaert '10

$$[\xi, \chi]_* \equiv [\xi, \chi]_{L.B.} - \delta_\xi \chi + \delta_\chi \xi$$

Asymptotic conserved charges

- we compute the charge difference between two backgrounds that differ via $\delta\mathcal{L}_{int}(u)$
- where $\delta\left(\mathcal{L}(u)\right) = \delta\mathcal{L}_{int}(u) + \mathcal{L}'(u)\delta u$ and $\delta u, \delta v$ are determined by the condition that $\delta U = \delta V = 0$
- can show winding part of the functions drops out of the final result

$$\not{\delta} Q_{f,\bar{f}} = \delta\Bigg[\underbrace{\frac{1}{2}\oint du\mathcal{L}(u)f_p(\hat{u})}_{Q_f} - \underbrace{\frac{1}{2}\oint dv\bar{\mathcal{L}}(v)\bar{f}_p(\hat{v})}_{\bar{Q}_{\bar{f}}}\Bigg] + \pi\left(c_{\bar{\mathcal{L}}_{\bar{f}}}\delta R_v + \delta c_{\bar{\mathcal{L}}} w_{\bar{f}} R_v - c_{\mathcal{L}_f}\delta R_u - \delta c_{\mathcal{L}} w_f R_u\right)$$

- where we assumed that $f_p, \bar{f}_p$ only depend on the fields via the combinations $\hat{u} \equiv \frac{u}{R_u}$, $\hat{v} \equiv \frac{v}{R_v}$
- integrability conditions: 1) set all c's to zero → unrescaled (Fourier basis) generators

2) $c_{\mathcal{L}} = c_{\bar{\mathcal{L}}} = 0\,, \quad c_{\mathcal{L}_f} = -\frac{Q_f}{\pi R_u}\,, \quad c_{\bar{\mathcal{L}}_{\bar{f}}} = \frac{\bar{Q}_{\bar{f}}}{\pi R_v}$ rescaled generators

labeled by functions $R_u \hat{f}_p(\hat{u}), R_v \hat{\bar{f}}_p(\hat{v})$

The charge algebra

- need to compute $\delta_\chi Q_\xi = \oint \boldsymbol{k}_\xi(\mathcal{L}_\chi \Phi, \Phi)$ for some other allowed diffeomorphism $\chi_{g,\bar{g}}$
- while $\delta_\chi \mathcal{L}$ is given, $\delta_\chi \mathcal{L}_{int}$ depends on the chosen basis: integrability fixes different constants

  → different results for the charge algebra, as expected

- algebra of the rescaled generators is $\text{Virasoro}_L \times \text{Virasoro}_R$ with same **c** as undeformed CFT

MG, Monten '19

$T\overline{T}$ – deformed CFTs = "non-local CFTs"

- algebra of the unrescaled generators (natural Fourier basis)

$$i\{Q_m, Q_n\} = \frac{1}{1+\mu H_R/\pi}(m-n)Q_{m+n} + \frac{\mu^2 H_R}{\pi^2(1+\mu H/\pi)(1+\mu H_R/\pi)}(m-n)Q_m Q_n + \mathcal{K}\,\delta_{m+n}$$

$$i\{Q_m, \bar{Q}_n\} = -\frac{\mu(m-n)}{\pi(1+\mu H/\pi)} Q_m \bar{Q}_n$$

Georgescu, MG '22

- precisely agrees with results of field theory analysis

MG, Monten, Tsiares '22

rescaled generators = original CFT generators transported along $T\overline{T}$ flow

Partial conclusions

- TT – deformed CFTs possess Virasoro x Virasoro symmmetry, despite their non-locality
- confirmed by field therory analyses ← full quantum definition of the generators
- this Virasoro acts differently from standard CFTs: $L_0, \bar{L}_0$ are non-linear functions of $H_{L,R}$
- algebra in natural Fourier basis = non-linear modification of Virasoro x Virasoro
- action of these symmetries on operator has yet to be understood (field theory)
- would now like to show the same symmetry algebra appears for the asymptotic linear dilaton background, up to a factor related to the symmetric product orbifold

Asymptotic symmetries of the asymptotically linear dilaton background

Setup

- as we anticipate field-dependent symmetries → turn on non-trivial background to see this

- we thus consider the asymptotically linear dilaton black hole backgrounds $p \leftrightarrow N_1$

$$d\bar{s}^2 = \frac{r^2}{\alpha' r^4 + \beta r^2 + \alpha' L_u L_v}\left(r^2 dU dV + L_u dU^2 + L_v dV^2 + \frac{L_u L_v}{r^2} dU dV\right) + k\frac{dr^2}{r^2}$$

$$e^{2\bar{\phi}} = \frac{kr^2}{\alpha' r^4 + \beta r^2 + \alpha' L_u L_v} \qquad \beta = \sqrt{p^2 + 4\alpha'^2 L_u L_v}$$

- using a consistent truncation to 3d

$$ds^2 = ds_3^2 + \ell^2 ds_{S_3}^2 \ , \qquad H = 2\ell^2\, \omega_{S^3} + b\, e^{2\phi}\, \omega_3$$

- classified linearized perturbations of this background: pure diffeos + propagating

- allowed diffeos : their symplectic form with the allowed modes, notably $\delta L_{u,v}$ must vanish

  → charge conservation $\boldsymbol{\omega}[\Phi, \delta_\xi \Phi, \delta\Phi] = d\boldsymbol{k}_\xi[\Phi, \delta\Phi]$

Allowed diffeomorphisms

- we choose diffeos that preserve the radial metric in Einstein frame

$$\xi^E_{rad} = \left(F_U(U,V) + \frac{k(r^2\,\partial_V F_r - L_v\,\partial_U F_r)}{r^4 - L_u L_v} \right) \partial_U + \left(F_V(U,V) + \frac{k(r^2\,\partial_U F_r - L_u\,\partial_V F_r)}{r^4 - L_u L_v} \right) \partial_V + \frac{r^3 F_r(U,V)}{\acute{r}^4 + r^2 \pm \acute{L}_u L_v} \partial_r$$

- symplectic form imposes:

$$F_U = f\,(u) + \frac{2\alpha' L_v}{p+\beta}\,\bar{f}\,(v) + c_U \;, \qquad F_V = \bar{f}\,(v) + \frac{2\alpha' L_u}{p+\beta}\,f\,(u) + c_V \qquad\qquad F_r = f_r(u) + \bar{f}_r(v)$$

where

$$u \equiv \frac{(p+\beta)\,U + 2\alpha' L_v V}{2p} \;, \qquad v \equiv \frac{(p+\beta)\,V + 2\alpha' L_u U}{2p}$$

- are identical with the $T\bar{T}$ field-dependent coord., upon using the TT parametrization (match energy)

$$L_u = \frac{\pi p\,\mathcal{L}}{1-\mu^2 \mathcal{L}\bar{\mathcal{L}}} \;, \qquad L_v = \frac{\pi p\,\bar{\mathcal{L}}}{1-\mu^2 \mathcal{L}\bar{\mathcal{L}}} \;, \qquad \alpha' = \frac{\mu}{\pi}$$

- integrability associated charges: choose c's to absorb zero modes of $f, \bar{f}$

- boundary metric fluctuates with $\delta g_{UU} = \frac{2\alpha' L_u}{\beta} \delta g_{UV} \;, \qquad \delta g_{VV} = \frac{2\alpha' L_v}{\beta} \delta g_{UV}$

Conserved charges and their algebra

- most charges vanish upon the constant backgrounds → deform the background $g = \bar{g} + \epsilon \mathcal{L}_\eta \bar{g}$

$$Q_{\xi_{f,\bar{f}}}[g] = \begin{cases} \mathcal{O}(1) & \text{for} \quad f, \bar{f} = const. \\ \mathcal{O}(\epsilon) & \text{for} \quad f, \bar{f} \neq const. \end{cases}$$

- conserved charge is identical to TT answer up to this order in the perturbation above constant bckgnds

$$\delta_\eta Q_\xi = \frac{1}{2} \int d\sigma \partial_\sigma u \left(2p\mathcal{L} f h' + \frac{k}{\pi} h_r'' f - \frac{k}{\pi} f_r'' h \right) + RM$$

provided we choose the radial functions as $f_r(u) = -\frac{p}{4} f'(u) \,, \qquad \bar{f}_r(v) = -\frac{p}{4} \bar{f}'(v)$

(not fixed by symplectic form analysis)

- this yields a central term in the algebra that is the same as that of a symmetric product orbifold of TT

$$\{Q_m, Q_{-m}\} = \frac{2m}{R_u} Q_0 + \frac{6kp}{12} \cdot \frac{m^3}{R_u^2} I$$

- to this order, can only compute 0^{th} order term in charge algebra, c.f. the rep. theorem $\delta_\chi Q_\xi = Q_{[\xi,\chi]_*}$

The algebra at the next order

- to see the non-trivial terms in the algebra, need to compute $\delta_\chi Q_\xi$ on the deformed backgrounds

$$g = \bar{g} + \epsilon \mathcal{L}_\eta \bar{g}$$

- need to consider the $\mathcal{O}(\epsilon)$ corrections to the diffeomorphisms χ, ξ

- fixed by :
  - symplectic form analysis upon the perturbed backgrounds
  - zeroth order representation theorem
  - "minimal continuation" assumption on the functions
  - periodicity of the fixed coordinates U, V → compensating winding contributions

ch. algebra:

$$i\{Q_m, Q_n\} = \frac{1}{1+\alpha' H_R/p}(m-n)Q_{m+n} + \frac{\alpha'^2 H_R}{p^2(1+\alpha' H/p)(1+\alpha' H_R/p)}(m-n)Q_m Q_n + \mathcal{K}\,\delta_{m+n}$$

$$i\{Q_m, \bar{Q}_n\} = -\frac{\alpha'(m-n)}{p(1+\alpha' H/p)} Q_m \bar{Q}_n$$

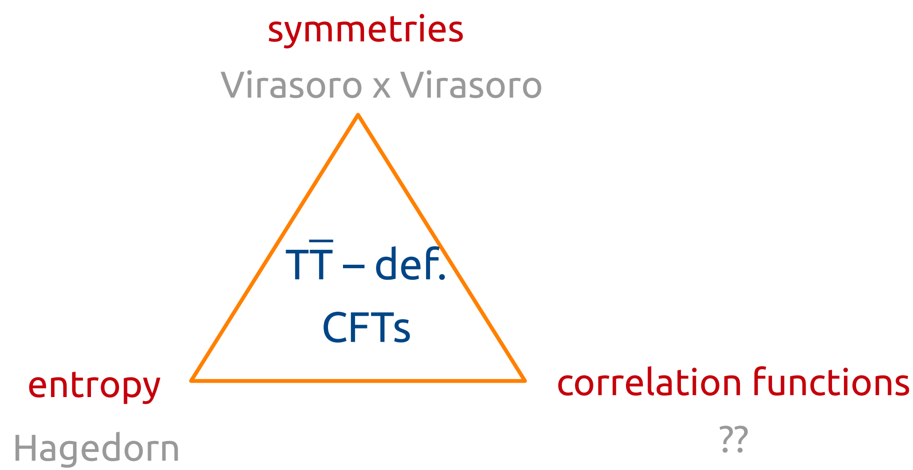
algebra of unrescaled TT generators up to $\mathcal{O}(\epsilon)$

- integrability is essential
- every step of the calc. is identical to its TT counterpart → bckgnds & bnd. cond. are entirely different!!

Conclusions

- we have shown that the asymptotic symmetries of the asymptotically linear dilaton background in string theory are precisely those of single-trace $T\bar{T}$ – deformed CFTs

- this further suggests the relevant "QFT structure" for these bckgnds is that of $T\bar{T}$ – deformed CFTs



- a better understanding of both field theory and gravity (both doable!) may pave the way for precision holography in this background

Thank you !