Extremal black holes and non-local CFTs

Monica Guica

Colloque IPhT 2018

Plan

- extremal black holes ↔ non-local generalizations of 2d CFTs (dipole CFTs)

- a promising concrete example of a 2d dipole CFT

Motivation

- HOLOGRAPHY

Quantum gravity

on $\mathcal{M}$

Gravitational theory

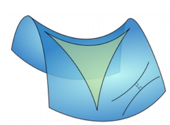
d+1 dimensions

universal

Field theory (no gravity)

d dimensions

usual Quantum Mechanics



- success story: $\mathcal{M}$ = AdS $_{d+1}$ ⟷ field theory = CFT$_d$

- Quantum gravity in the real world?

- $\mathcal{M}$ = de Sitter

dS/CFT ?

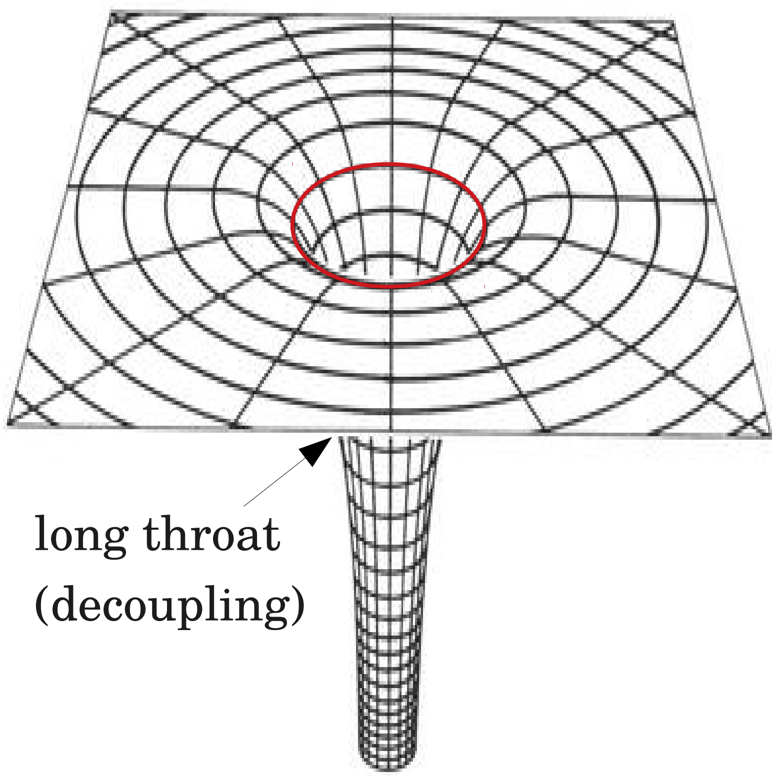
$\mathcal{M}$ = flat space

??

need new types of QFTs !

(non - local)

Holography and black holes



- black holes make holography easier to uncover

$$S_{BH} = \frac{\mathcal{A}_H}{4G}$$

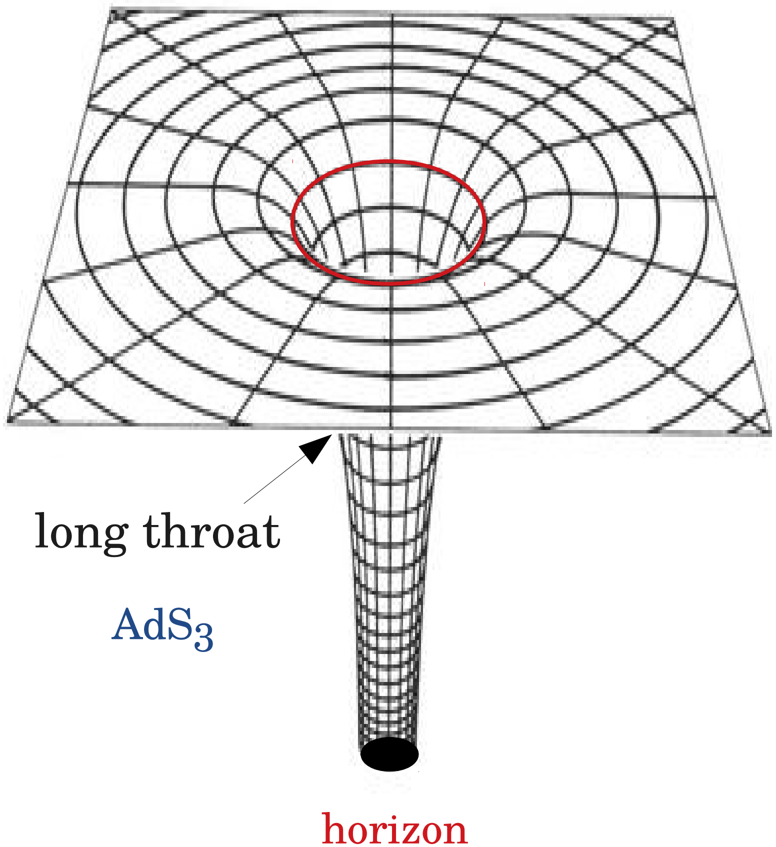
- find a microscopic system such that

$$S_{BH} = \ln \Omega_{micro}$$

- so far, only understood for black holes with an AdS_3 factor in the near-horizon region (AdS_3/ CFT_2)

- unrealistic, mostly string-theoretical black holes

AdS$_3$ black holes and 2d CFTs



$$L_0 = \frac{1}{2}(M + J)$$

$$\bar{L}_0 = \frac{1}{2}(M - J)$$

How to find the holographic dual to an AdS$_3$ black hole?

- isolate the throat/decoupled region
- compute asymptotic symmetry algebra at the throat boundary
- 2 copies of Virasoro algebra → 2d CFT !!

$$[L_m, L_n] = (m-n)L_{m+n} + \frac{c}{12}m(m^2-1)\delta_{m+n,0}$$

$c =$ central charge

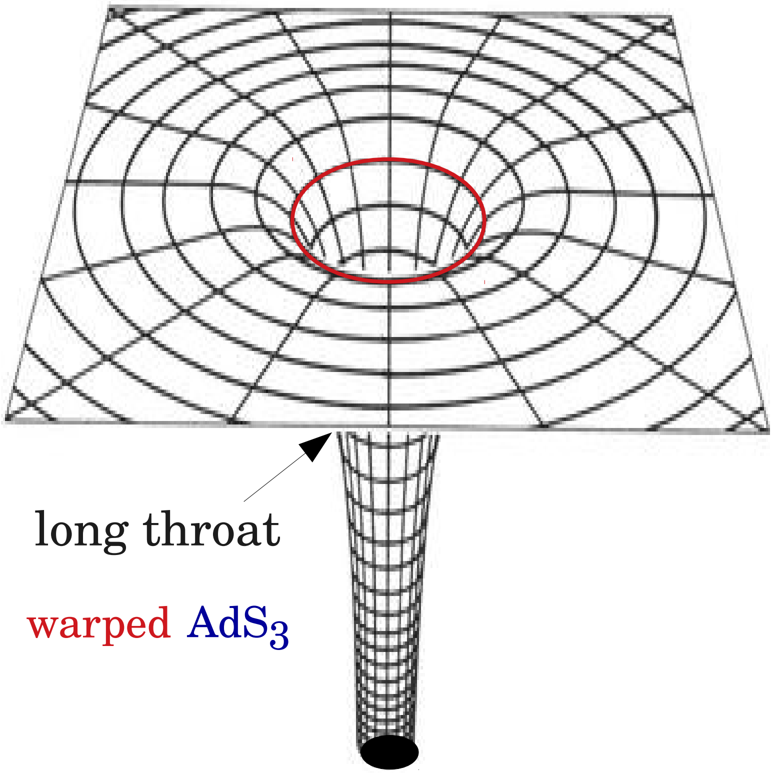
- check conjecture by computing entropy

$$S_{CFT} = \underbrace{2\pi\sqrt{\frac{c}{6}L_0} + 2\pi\sqrt{\frac{c}{6}\bar{L}_0}}_{\text{Cardy}} = S_{BH}$$

microscopic

- (many other checks)

Extremal black holes and 2d CFTs ?



universal

- vanishing surface gravity at the horizon
- can be realistic: extreme Kerr $GM^2 \simeq J$

  Cygnus X1 $J/GM^2 > 0.95$
- isolate the throat region: warped $AdS_3 \neq AdS_3$!!
- compute asymptotic symmetry algebra

$$[L_m, L_n] = (m-n)L_{m+n} + \frac{c}{12}m(m^2-1)\delta_{m+n,0}$$

Virasoro algebra → 2d CFT !!

- check conjecture by computing entropy

$$S_{Cardy} = S_{BH}$$

- however: conformal dimensions are momentum - dependent $h(\kappa)$ → non-local CFT ??!

“ dipole CFT ”

Some properties of dipole CFTs

- these properties are inferred from holography: we do not have a QFT definition!

- dipole CFTs are irrelevant deformations of CFTs by a spin 1 operator (~~Lorentz~~)

$$S_{dipole\,CFT} = S_{CFT} + \lambda \int d^2x\, \mathcal{O}_{(1,2)} + \ldots$$

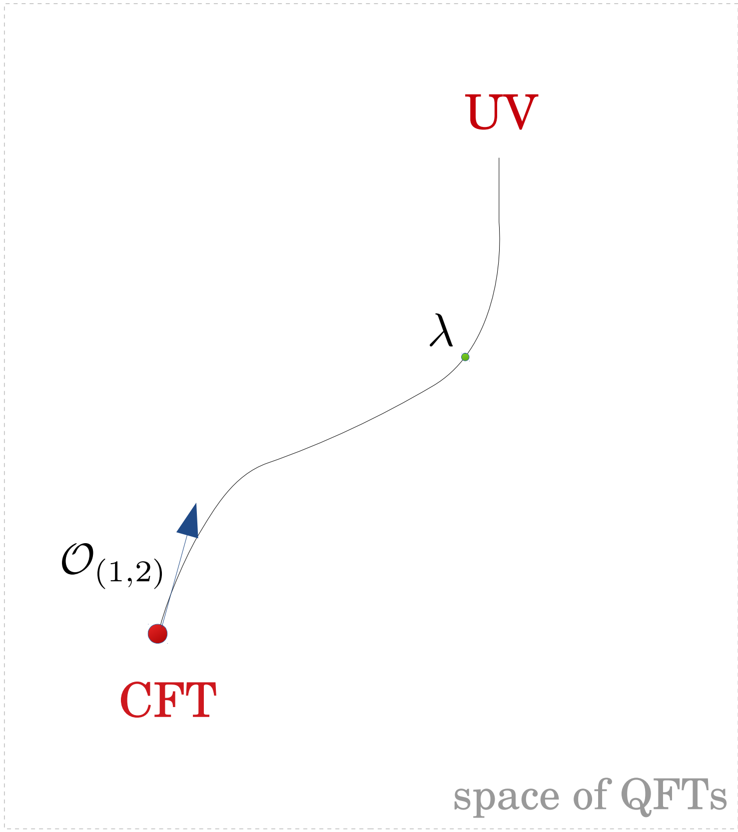
tunable

- symmetry $SL(2,\mathbb{R})_L \times U(1)_R$ $\leftarrow$ non-local

- same entropy as in a CFT (Cardy)

- Virasoro (???)

- non-local in the UV yet well-defined



- Example: null dipole-deformed $\mathcal{N} = 4$ super Yang-Mills (SYM) $\rightarrow$ 4d! Bergman, Ganor ‘00

Deformations of the Smirnov – Zamolodchikov type

and holography

The $T\overline{T}$ deformation

- 2d relativistic QFT, stress tensor $T_{ab} = T_{ba}$, $\partial^a T_{ab} = 0$

- special operator

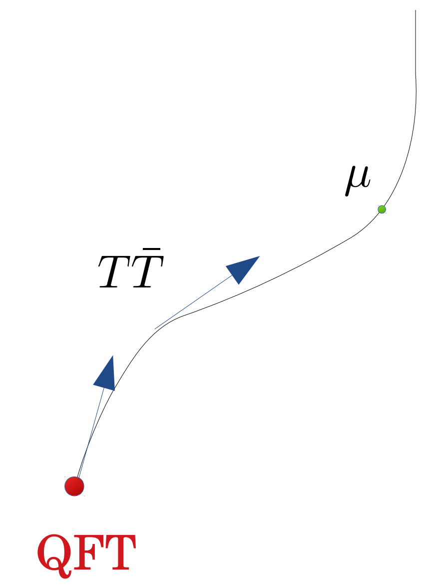
$$T\bar{T}(z) \equiv \lim_{z' \to z} T_{zz}(z')T_{\bar{z}\bar{z}}(z) - T_{z\bar{z}}(z')T_{z\bar{z}}(z)$$

- e.g. factorization in energy-momentum eigenstates

$$\langle n|T\bar{T}|n\rangle = \langle n|T_{zz}|n\rangle\langle n|T_{\bar{z}\bar{z}}|n\rangle - (\langle n|T_{z\bar{z}}|n\rangle)^2$$

- deform a 2d QFT by the $T\overline{T}$ operator $\frac{\partial S}{\partial \mu} = \int d^2z \, (T\bar{T})_\mu$

  (irrelevant)



- flow equation for spectrum on a cylinder $\rightarrow$ can be solved exactly (e.g. for deformed CFT)

$$\frac{\partial E(\mu, R)}{\partial \mu} = R\langle n|T\bar{T}|n\rangle = E(\mu, R)\frac{\partial E(\mu, R)}{\partial R} + \frac{P^2(R)}{R}$$

- $T\overline{T}$ preserves integrability $\rightarrow$ deformation of the S-matrix via TBA $\mathcal{S}(\mu) = e^{i\sum_{i,j}\mu\epsilon_{\alpha\beta}p_i^\alpha p_j^\beta}\mathcal{S}_0$

- theory non-local but well-defined UV $\rightarrow$ asymptotically fragile

Interesting applications

- QFT = 24 free bosons → worldsheet theory of the bosonic string $\mu = \ell_s^2$

  → 2d quantum gravity

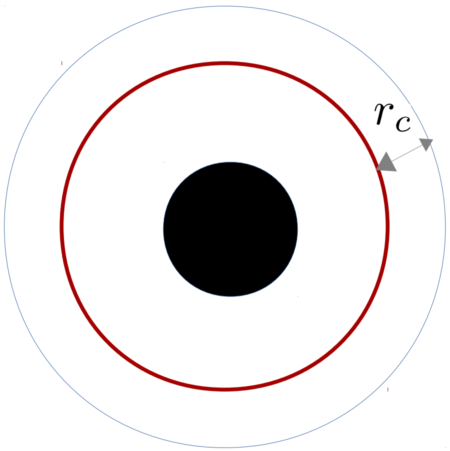
  Dubovsky et al.

- QFT = holographic CFT (dual to 3d Einstein gravity) and $\mu < 0$

  → holographically dual to AdS_3 gravity with a finite bulk cutoff $r_c = \sqrt{|\mu|}$

  → perfect match of energy spectrum cut off at high energies

  Verlinde et al.



- variation: QFT = Sym $(CFT)^N$ $\quad T\bar{T}' = \sum_{i=1}^{N} T_i \bar{T}_i$

  → holographically dual to a linear dilaton background

  (little string theory – matches Hagedorn behaviour

  Kutasov et al.

The $J\bar{T}$ deformation

- many deformations with similar properties to $T\bar{T}$: factorization, integrability

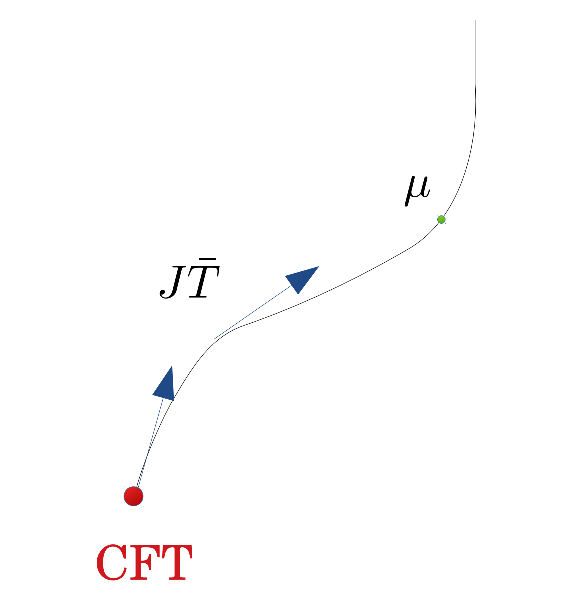
$$\frac{\partial S_{J_1,J_2}}{\partial \mu} = \int d^2 z (J_1 \bar{J}_2 - J_2 \bar{J}_1)$$

- another universal deformation: consider 2d CFT with a $U(1)$ current, J

$$\frac{\partial S_{J\bar{T}}}{\partial \mu} = \int d^2 z \, (J_z T_{\bar{z}\bar{z}} - J_{\bar{z}} T_{z\bar{z}})$$

$(1,2)$

- breaks Lorentz invariance
- preserves $SL(2,\mathbb{R})_L \times U(1)_R$ ← non-local
- deformation irrelevant but integrable
- expected UV complete
- simplest example of a 2d dipole CFT



Some properties of J$\bar{\text{T}}$ – deformed CFTs

- spectrum on the cylinder (J chiral → universal)

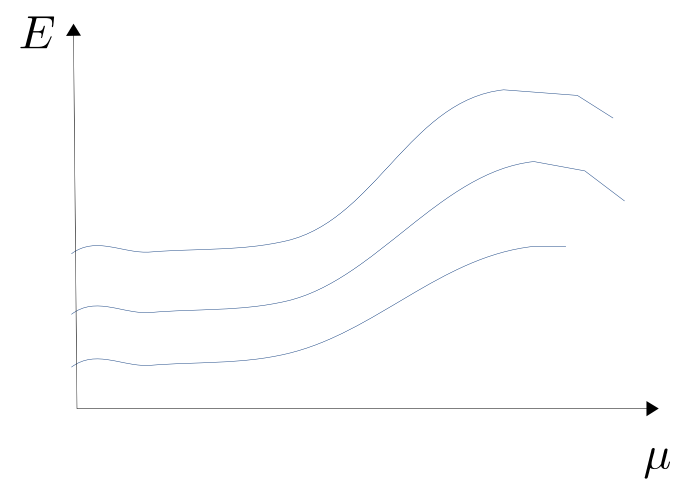
chiral anomaly

$$\frac{\partial E_n}{\partial \mu} = R\langle n|J\bar{T}|n\rangle \, , \qquad \frac{\partial Q_n}{\partial \mu} = \frac{k}{4\pi} R\langle n|\bar{T}|n\rangle$$

- $k=0$ breaks down for $R < \mu Q$ (energies diverge, closed timelike curves)

- $k \neq 0$ spectrum cut off at high energies $\bar{h}_{max} = \frac{1}{\mu^2 k}(R-\mu Q_0)^2$

- thermodynamics: energy levels smoothly deformed



→ number of states stays the same

$$S_{Cardy}(h,\bar{h}) \to S_{Cardy}(h(E,P,\mu),\bar{h}(E,P,\mu))$$

→ thermodynamics quantites break down as above

Holography

- gauge systems with a large N expansion (e.g. $SU(N)$, $\mathcal{S}_n$)
- $J\bar{T}$ is a double-trace deformation → mixed boundary conditions for dual bulk fields
- AdS_3/CFT_2 dictionary

$T_{\alpha\beta} \leftrightarrow g_{\alpha\beta}$ 3d graviton ← non-dynamical $T^a{}_\alpha \leftrightarrow e^a{}_\alpha$

$J_\alpha \leftrightarrow A_\alpha$ Chern-Simons gauge field ← non-dynamical

- mixed boundary conditions are $e_a^\alpha = \delta_a^\alpha + \mu_a \langle J^\alpha \rangle$, $A_\alpha = \mu_a \langle T_\alpha^a \rangle$
- holographic dictionary yields $\langle \tilde{J}^\alpha \rangle, \langle \tilde{T}_\alpha^a \rangle$ in the deformed theory

→ perfect match between energies of black holes and the defomed CFT spectrum

→ precision holography

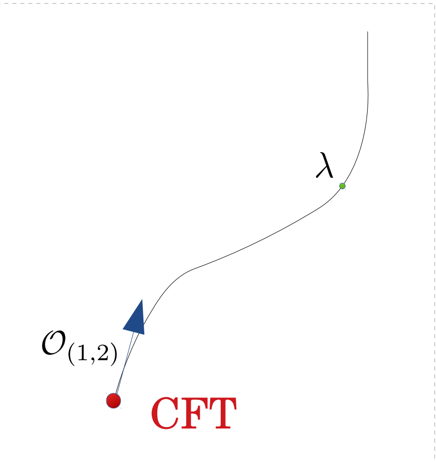
- asymptotic symmetry group analysis $U(1)_J \times SL(2,\mathbb{R})_L \times U(1)_R$

$\underbrace{U(1)_J \times SL(2,\mathbb{R})_L}_{\text{Virasoro Kač-Moody}}$; $U(1)_R$ → non-local Virasoro !?

Future directions

- $SL(2,\mathbb{R})_L$ invariance $\rightarrow$ 1d CFT structure $\mathcal{O}_I(z,\bar{p})$ $\leftarrow$ conformal data $h_I(\bar{p}), C_{IJK}(\bar{p}_I)$
- deforming operator $J\bar{T}$ $\leftarrow$ correlators determined by Ward identities

  $\rightarrow$ can we fully specify the deformed correlation functions ? (via CPT)
- understand origin of cutoff in the finite-size spectrum at high energies $\rightarrow$ superradiance
- single-trace analogue of the $J\bar{T}$ deformation? $\rightarrow$ holographic dual to warped AdS_3
- meaning of the non-local Virasoro?
- Cardy formula for warped AdS_3 black holes?
- S-matrix description of the $J\bar{T}$ deformation?



- definition of most general 2d dipole CFT? $S_{dipole\,CFT} = S_{CFT} + \lambda \int d^2x\, \mathcal{O}_{(1,2)} + \ldots$

  $\rightarrow$ constraints on original CFT, completion to higher orders, spectra, symmetries...

Thank you!