

Title: Asymptotic entanglement and celestial holography

Speakers: Hong Zhe Chen

Series: Quantum Fields and Strings

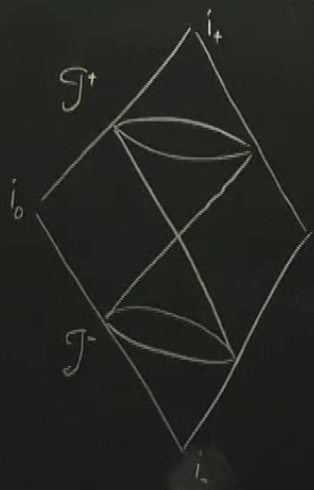
Date: June 09, 2023 - 11:00 AM

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Abstract: While entanglement has been examined extensively in AdS/CFT, it has avoided significant attention in the study of celestial holography and asymptotic symmetries relevant to asymptotically flat spacetime. I will present work that considers the entanglement of a Milne patch for Maxwell theory in Minkowski spacetime from the perspective of celestial holography. In the Minkowski vacuum, we find that the Milne patch is thermally entangled. We interpret the thermal entangling operator that builds the Minkowski vacuum from the Milne vacuum as an interaction term in the celestial CFT. We further examine the edge modes of the Milne patch, assigning them a physical interpretation as fluctuations in Milne asymptotic charge. Interestingly, we find that the constraint governing these edge modes includes sources that avoid the Minkowski interior. Altogether, by studying entanglement along the extra holographic direction present in celestial holography but absent in AdS/CFT, our work bridges a critical gap between our understanding of entanglement in the latter and the physically relevant setting of asymptotically flat spacetime.

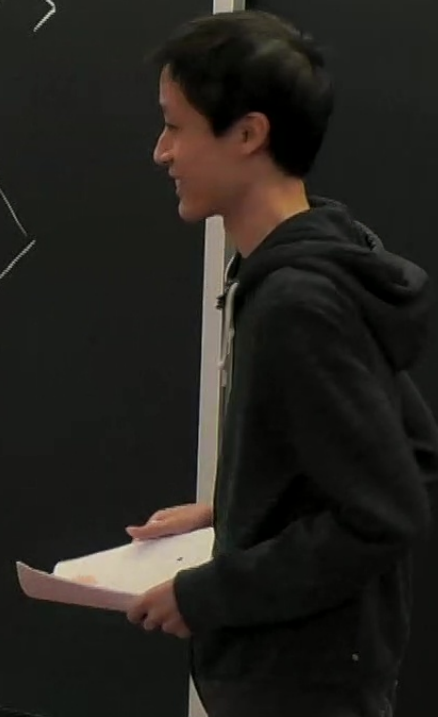
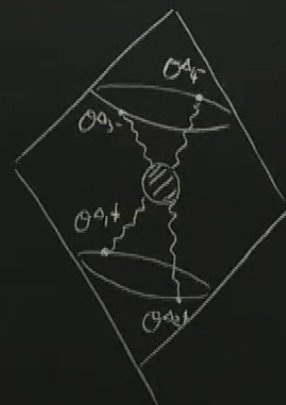
Zoom Link: TBD

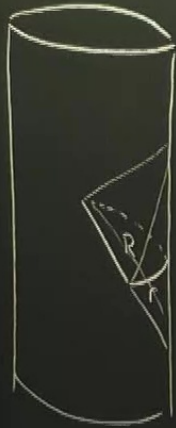
# SPACETIME ENTANGLEMENT IN CELESTIAL HOLOGRAPHY



$R^{1,3} \leftrightarrow \text{CCFT}_2$   
 Lorentz  $\leftrightarrow$  Conformal symm  
 entanglement of  $R \leftrightarrow ?$   
 $R \leftrightarrow ?$

$\langle \mathcal{O}^{\Delta_1, -}, \dots, \mathcal{O}^{\Delta_n, +} \rangle$





$$\text{AdS}_{d+1} \leftrightarrow \text{CFT}_d$$

isometries  $\leftrightarrow$  conformal symm.

$$S_{\text{gen}}(R) \leftrightarrow S(r)$$


$$R \leftrightarrow r$$

$$\langle \mathcal{O}_{\Delta_4} \dots \mathcal{O}_{\Delta_1} \rangle_{\text{CFT}} =$$



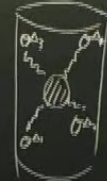
ENTANGLEMENT  
AL HOLOGRAPHY

$R^{1,2} \leftrightarrow \text{eCFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 entanglement of  $R$  as?  
 $R \leftrightarrow ?$




$AdS_{2+1} \leftrightarrow \text{CFT}_d$   
 isometries  $\leftrightarrow$  conformal symm  
 $S_{\text{gen}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

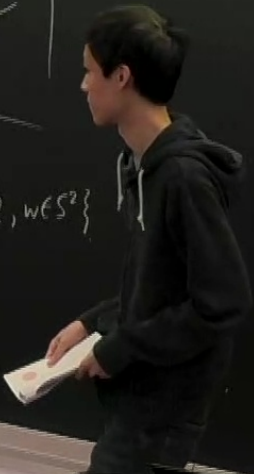
$\langle O^{\Delta_1} \dots O^{\Delta_n} \rangle_{\text{CFT}} =$





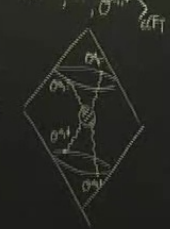
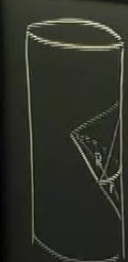
$A^\Delta =$  eigenfunc of boost,  
 with eigenval  $\Delta$

$\text{span} \{ e^{ik \cdot X} \}$   
 $= \text{span} \{ A^\Delta(w) \mid \Delta = 1 + i\lambda, \lambda \in \mathbb{R}, w \in S^2 \}$



ENTANGLEMENT  
AND HOLOGRAPHY

$R^{1,3} \leftrightarrow \text{eCFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 entanglement of  $R \leftrightarrow ?$   
 $R \leftrightarrow r$

$AdS_{2,1} \leftrightarrow CFT_1$   
 isometries  $\leftrightarrow$  conformal symm  
 $S_{\text{geo}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

$\langle O^{\Delta_1} \dots O^{\Delta_n} \rangle_{CFT} =$



$A_{a,r}^{\Delta}(w,X) = K_{a,r}^{\Delta}(w,X) = \frac{1}{(-\frac{1}{2}(w,X))^{\Delta}}$   
 $\hat{g}(w) = \frac{1}{2}(1 + w\bar{w}, w + \bar{w}, -i(w - \bar{w}), 1 - w\bar{w})$



$A^{\Delta}$  = eigenfunc of boost,  
 with eigenval.  $\Delta$

$\text{span} \{ e^{ik \cdot X} \mid k^0 > 0 \}$   
 $= \text{span} \{ A_{a,r}^{\Delta}(w) \mid \Delta = 1 + i\lambda, \lambda \in \mathbb{R}, w \in S^2 \}$

$A(X) = \int_{-\infty}^{\infty} d\lambda \int d^2w \left( A_{a,r}^{1+i\lambda, r}(w,X) \left( \frac{1-i\lambda}{\lambda w} \right) + \dots \right)$



ENTANGLEMENT  
AL HOLOGRAPHY

$R^{1,2} \leftrightarrow \text{CFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 extension of  $R$  as?  
 $R \leftrightarrow ?$

$AdS_{3+1} \leftrightarrow \text{CFT}_4$   
 isometries  $\leftrightarrow$  conformal sym  
 $S_{\text{gen}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

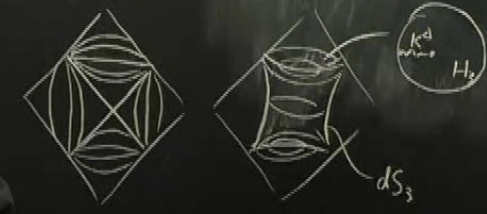
$\langle \mathcal{O}_{\Delta_1} \dots \mathcal{O}_{\Delta_n} \rangle_{\text{CFT}} =$

$A_{\Delta, \mu}^\Delta(w, X) = K_{\Delta, \mu}^\Delta(w, X)$

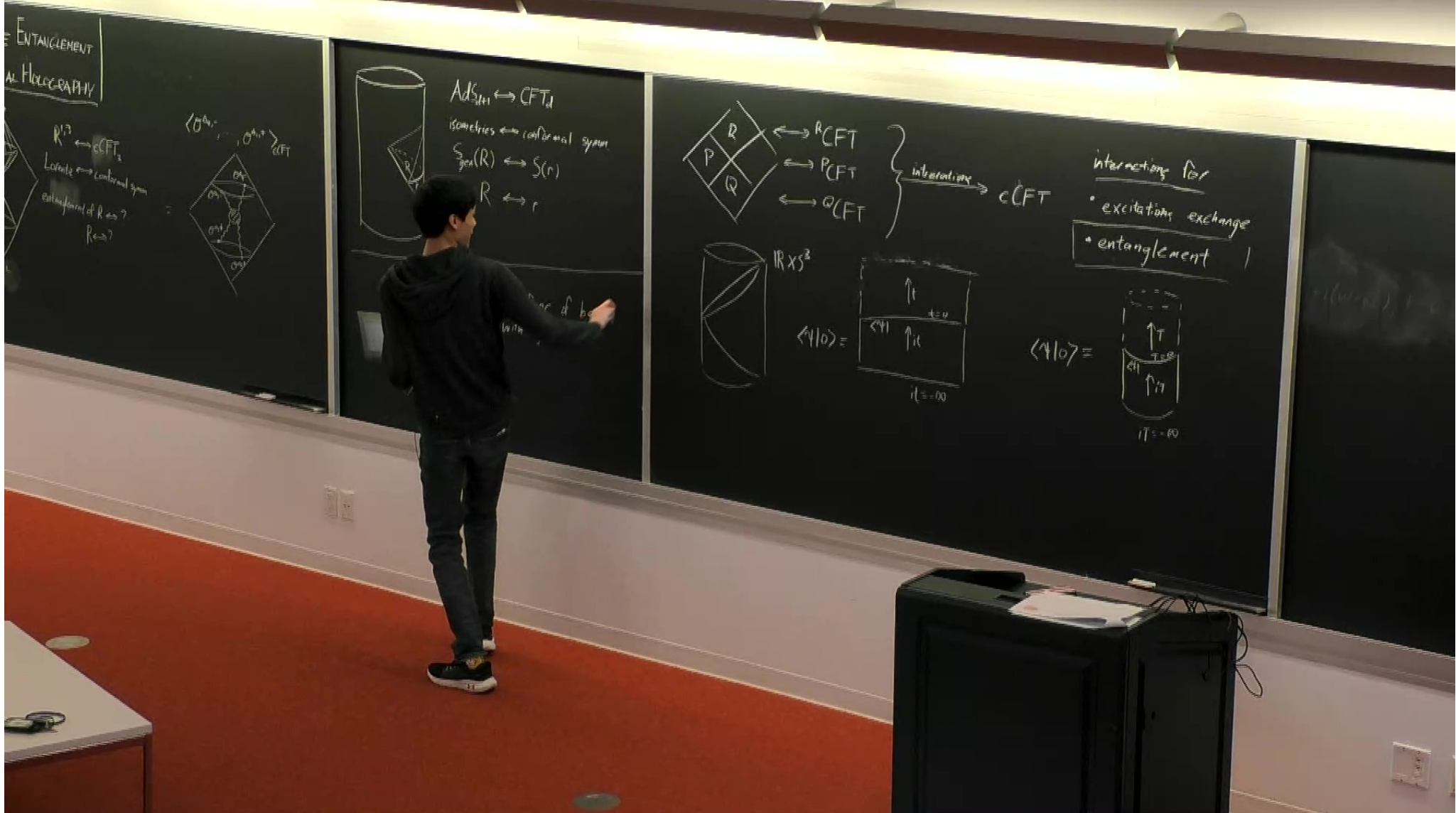
$A^\Delta =$  eigenfunc of boost,  
 with eigenval:  $\Delta$

$\text{span} \{ e^{ik \cdot X} \mid k^0 > 0 \}$   
 $= \text{span} \{ A_{\Delta, \mu}^\Delta(w) \mid \Delta = 1 + i\lambda, \lambda \in \mathbb{R} \}$

$A(X) = \int_{-\infty}^{\infty} d\lambda \int d^2 w \dots$



$A_{\Delta, \mu}^\Delta(w, X) \propto (w)^\Delta$



ENTANGLEMENT  
AL HOLOGRAPHY

$R^{1,2} \leftrightarrow \text{eCFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 Entanglement of  $R \leftrightarrow ?$   
 $R \leftrightarrow ?$

$\langle O^{A_1}, \dots, O^{A_n} \rangle_{\text{CFT}}$

$AdS_{2n+1} \leftrightarrow \text{CFT}_n$   
 isometries  $\leftrightarrow$  conformal symm  
 $S_{\text{gen}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

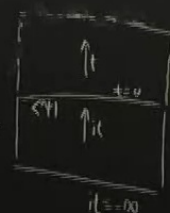
of  $b$


$\begin{matrix} R \\ P \\ R \end{matrix}$   $\leftrightarrow$  RCFT  
 $\leftrightarrow$  PCFT  
 $\leftrightarrow$  QCFT

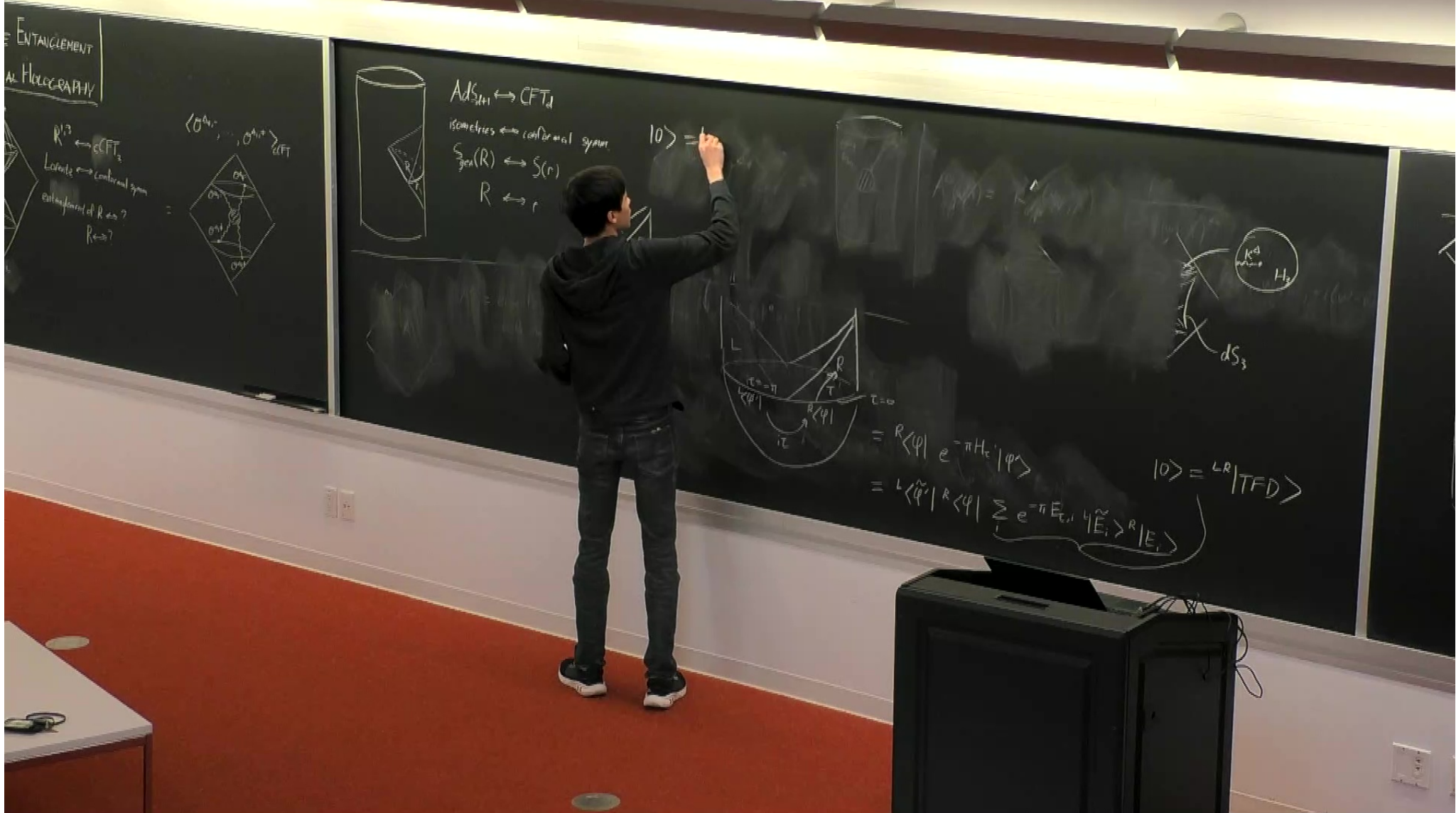
interactions  $\rightarrow$  eCFT

interactions for  
 • excitation exchange  
 • entanglement

$\mathbb{R} \times S^2$

$\langle \psi | \psi \rangle =$  

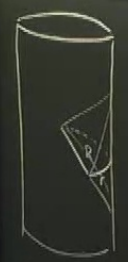
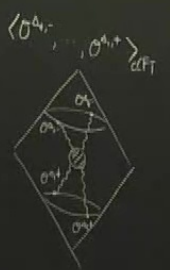
$\langle \psi | \psi \rangle =$  





ENTANGLEMENT  
AL HOLOGRAPHY

$R^{1,2} \leftrightarrow \text{CFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 entanglement of  $R$  as?  
 $R \leftrightarrow r$

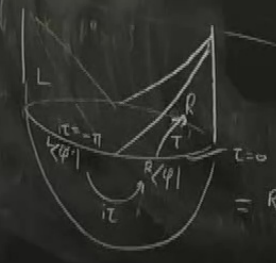


$AdS_{2+1} \leftrightarrow CFT_d$   
 isometries  $\leftrightarrow$  conformal symm  
 $S_{\text{gen}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

$$|0\rangle = |LR\rangle |TFD\rangle \propto \sum_i e^{-\pi E_i} |\tilde{E}_i\rangle^R |E_i\rangle$$



$$\langle \tilde{\phi} | \phi \rangle_{|0\rangle} =$$



$$= {}_R \langle \phi | e^{-\pi H_L} | \phi \rangle$$


$$= {}_L \langle \tilde{\phi} | {}_R \langle \phi | \sum_i e^{-\pi E_i} |\tilde{E}_i\rangle^R |E_i\rangle$$

$$|0\rangle = |LR\rangle |TFD\rangle$$

ENTANGLEMENT  
 Holography

$R^{1,2} \leftrightarrow \text{CFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 entanglement of  $R$  in?  $R \leftrightarrow r$

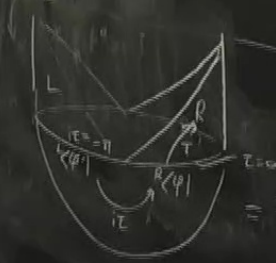
$\langle O^{A_1}, \dots, O^{A_n} \rangle_{\text{CFT}}$




$AdS_{2+1} \leftrightarrow CFT_3$   
 isometries  $\leftrightarrow$  conformal symm  
 $S_{\text{geo}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

$|0\rangle = LR|TFD\rangle \propto \sum_i e^{-\pi E_i} |\tilde{E}_i\rangle^R |E_i\rangle$

$A = \int_0^\infty dt \int d^2w \left( R A_a^{1+i\epsilon}(w) (b^{1-i\epsilon})^\dagger(w) + (\dots)^\dagger \right)$   
 $L \tilde{A}_a^{1-i\epsilon}(w) (L^{1+i\epsilon})^\dagger(w) + (\dots)^\dagger$

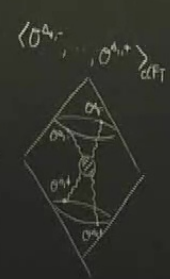


$\langle \psi | \rho | \psi \rangle =$   
 $= R \langle \psi | e^{-\pi H_L} | \psi \rangle$   
 $= L \langle \tilde{\psi} | R \langle \psi | \sum_i e^{-\pi E_i} |\tilde{E}_i\rangle^R |E_i\rangle$



ENTANGLEMENT  
AL HOLOGRAPHY

$R^{1,2} \leftrightarrow \text{CFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 entanglement of R as?  
 $R \leftrightarrow r$




$AdS_{2+1} \leftrightarrow CFT_d$   
 isometries  $\leftrightarrow$  conformal sym  
 $S_{\text{gen}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

$|0\rangle = LR|TFD\rangle \propto \sum_i e^{-\pi E_i} |E_i\rangle^R |E_i\rangle^L$

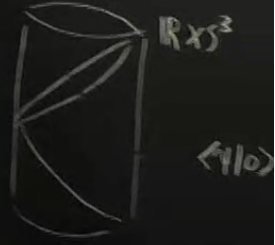
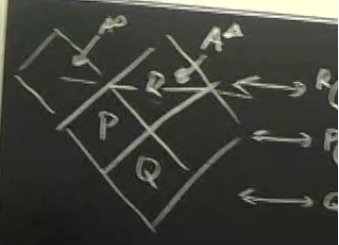


$A = \int_0^\infty dt \int d^2w (R A_a^{11+2}(w) L \tilde{A}_a^{1-12}(w))$

$A^\Delta = e^{\pm i\pi(\Delta-1)} L \tilde{A}^\Delta + R \tilde{A}^\Delta$   
 $\alpha^{-1-i\epsilon}$

$\langle \bar{\psi} | \psi | 0 \rangle =$

$L \tilde{A}^\Delta = -i\lambda$   
 $= R \langle \psi | e^{-\pi H_\epsilon} | \psi \rangle$   
 $= L \langle \bar{\psi} | R \langle \psi | \sum e^{-\pi}$





ENTANGLEMENT  
AL HOLOGRAPHY

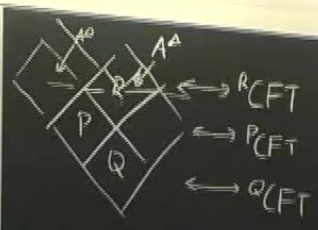
$R^{1,2} \leftrightarrow \text{cCFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 Entanglement of  $R$  as?  
 $R \leftrightarrow r$

$\langle \mathcal{O}^{A_1}, \dots, \mathcal{O}^{A_n} \rangle_{\text{CFT}}$

$AdS_{3+1} \leftrightarrow \text{CFT}_4$   
 isometries  $\leftrightarrow$  conformal sym  
 $S_{\text{gen}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow r$

$|0\rangle =$

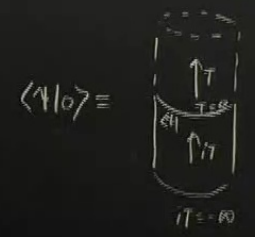
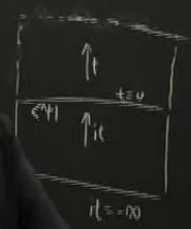
$\langle \mathcal{O}^A | \mathcal{O}^B | 0 \rangle =$

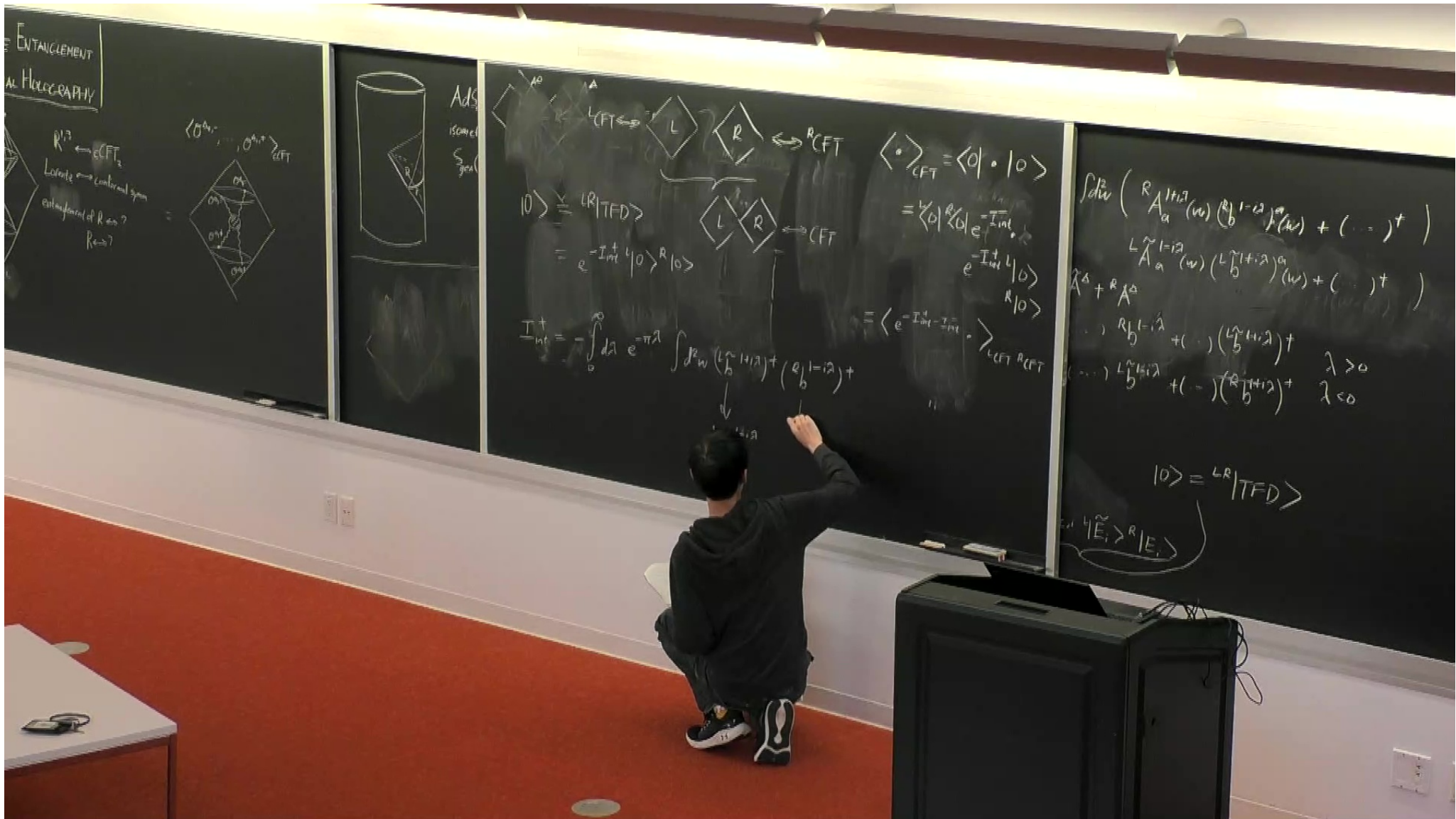


$\left. \begin{matrix} \leftrightarrow \text{RCFT} \\ \leftrightarrow \text{PCFT} \\ \leftrightarrow \text{QCFT} \end{matrix} \right\} \text{interactions} \rightarrow \text{cCFT}$

interactions for

- excitations exchange
- entanglement

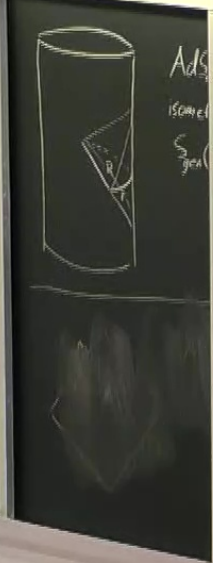




ENTANGLEMENT  
AL HOLOGRAPHY

$R^{1,2} \leftrightarrow \text{eCFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 entanglement of R  $\leftrightarrow$  ?  
 $R \leftrightarrow ?$

$\langle 0^{A_1}, \dots, 0^{A_n} \rangle_{\text{CFT}}$



AdS

$L \leftrightarrow R \leftrightarrow \text{CFT}$

$|0\rangle \equiv |LR\rangle_{\text{TFD}}$   
 $= e^{-I_{\text{int}}} |0\rangle^R |0\rangle^L$

$I_{\text{int}}^+ = - \int_0^{\beta} d\lambda \int d^2 w (L_b^{H, \lambda})^+ + (e_b^{1-i\lambda})^+$

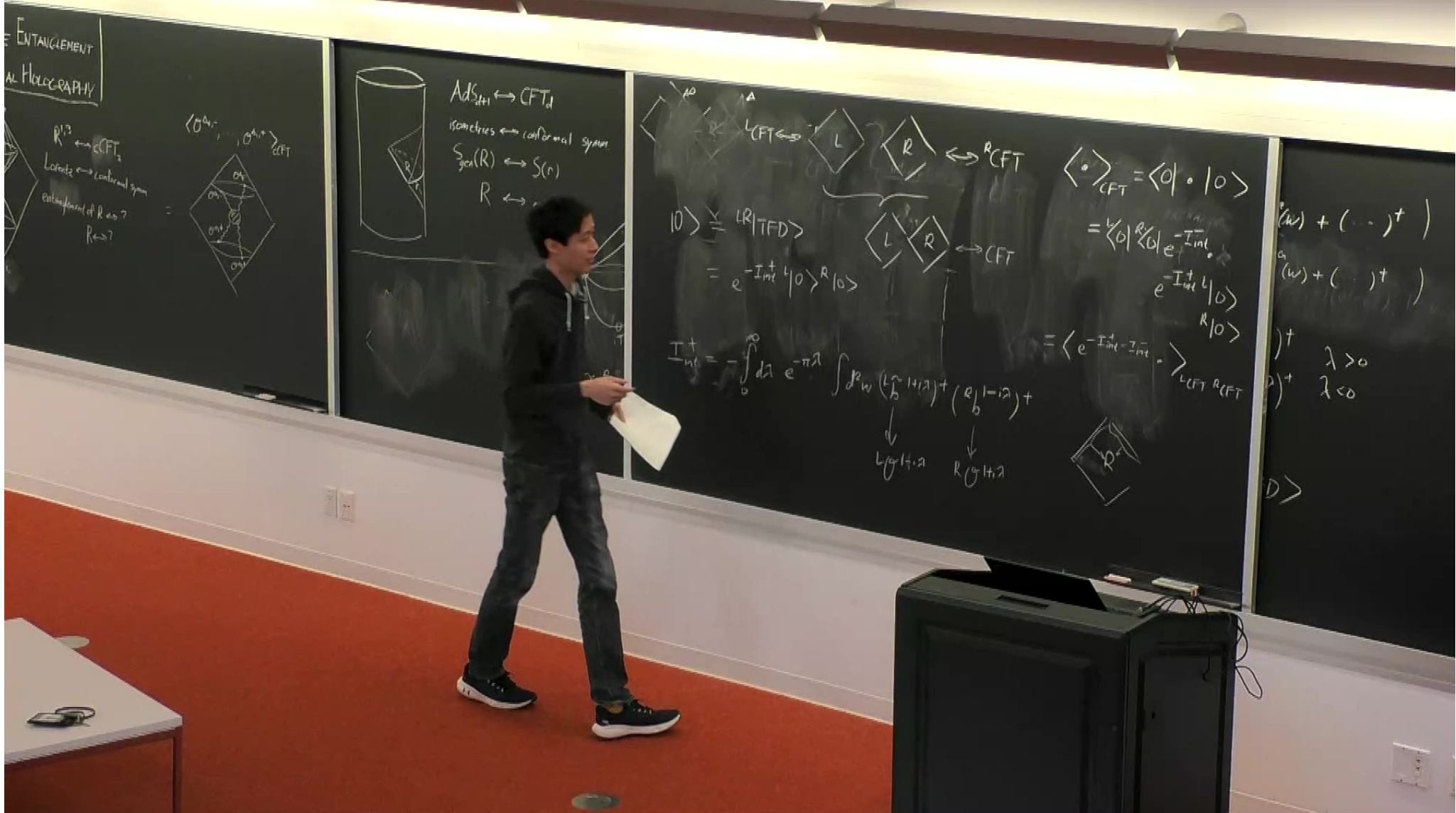
$\langle \cdot \rangle_{\text{CFT}} = \langle 0 | \cdot | 0 \rangle$   
 $= \langle 0^R | \langle 0^L | e^{-I_{\text{int}}} | 0 \rangle$   
 $= \langle e^{-I_{\text{int}}^+} | 0 \rangle^R | 0 \rangle^L$   
 $= \langle e^{-I_{\text{int}}^+ - I_{\text{int}}^-} \cdot \rangle_{\text{CFT}^R \text{CFT}^L}$

Solve  $(R A_a^{H, \lambda}(w) (R_b^{1-i\lambda})^+(w) + (\dots)^+)$   
 $L A_a^{H, \lambda}(w) (L_b^{1+i\lambda})^+(w) + (\dots)^+$

$\lambda^A + R A^A$   
 $\dots, R_b^{1-i\lambda} + (\dots) (L_b^{H, \lambda})^+$   
 $\dots, L_b^{H, \lambda} + (\dots) (R_b^{1+i\lambda})^+$

$\lambda > 0$   
 $\lambda < 0$

$|0\rangle = |LR\rangle_{\text{TFD}}$   
 $\sim |E_i\rangle^R |E_i\rangle^L$



ENTANGLEMENT  
AL HOLOGRAPHY

$R^{1,2} \leftrightarrow \text{CFT}_2$   
 Lorentz  $\leftrightarrow$  conformal sym  
 entanglement of R as?  
 $R \leftrightarrow ?$

$\langle O^{A_1}, \dots, O^{A_n} \rangle_{\text{CFT}}$

$AdS_{d+1} \leftrightarrow CFT_d$   
 isometries  $\leftrightarrow$  conformal sym  
 $S_{\text{gen}}(R) \leftrightarrow S(r)$   
 $R \leftrightarrow ?$

$L \leftrightarrow R \leftrightarrow R\text{CFT}$   
 $L \leftrightarrow R \leftrightarrow \text{CFT}$

$|0\rangle \equiv |LR|_{\text{TFD}}\rangle$   
 $= e^{-I_{\text{int}}^+} |0\rangle^R |0\rangle^L$

$I_{\text{int}}^+ = -\int_0^{\beta} d\lambda e^{-\pi\lambda} \int d^2w (L_b^{-1+i\lambda})^+ (R_b^{1-i\lambda})^+$   
 $\downarrow \quad \downarrow$   
 $L/g_{H,2} \quad R/g_{H,2}$

$\langle \bullet \rangle_{\text{CFT}} = \langle 0 | \bullet | 0 \rangle$   
 $= \langle 0 |^R \langle 0 |^L e^{-I_{\text{int}}^+}$   
 $e^{-I_{\text{int}}^+} |0\rangle^L |0\rangle^R$   
 $= \langle e^{-I_{\text{int}}^+ - I_{\text{int}}^-} \rangle_{L\text{CFT} R\text{CFT}}$

$(w) + (\dots)^+$   
 $(w) + (\dots)^+$   
 $)^+ \quad \lambda > 0$   
 $)^+ \quad \lambda < 0$   
 $|D\rangle$