Title: Asymptotically isometric codes

Speakers: Thomas Faulkner

Series: Quantum Fields and Strings

Date: May 23, 2023 - 2:00 PM

URL: https://pirsa.org/23050022

Abstract: I review a class of quantum error correcting codes that directly takes into account the large-N aspects of holographic theories. I will discuss some aspects of the vacuum sector of these codes and use them to show the equivalence between two different approaches to entanglement wedge reconstruction.

Zoom link: https://pitp.zoom.us/j/96318197584?pwd=YXJEdkJrVktXVmI3SWVlRmlaK3A4Zz09

Asymptotically Isometric Codes: 2211.12439

w/ Min Li

Plan:
- Summary of AIC
- equivilence of QEC reconstruction & mod. flow "
- Vacuum codes & the split [preliminary]

Math Pre-req.'s : $\mathcal{H}$, $L(\mathcal{H})$ $\longrightarrow$ type I_n von Neumann Alg.

$n = \dim(\mathcal{H})$

* In finite dimensions we have norm

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* In finite dimensions we have norm equivilence : $a \in B(\mathcal{H})$

$$\|a\| = \max \text{ e-value } |a| \equiv \sqrt{a^\dagger a}$$

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Aic

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$n = \dim(\mathcal{K})$

- In finite dimensions we have norm equivalence: $a \in B(\mathcal{K})$

$$\|a\| = \text{max e-value } |a| \equiv \sqrt{a^\dagger a}$$

$$\|a\|_1 = \operatorname{tr}|a| \qquad \|a\|_2 = \sqrt{\operatorname{tr}|a|^2}$$

$$\|a\|_\infty = (\operatorname{tr}|a|^p)^{1/p} \quad p \to \infty$$

$a_n \to 0$ in $\|a\|$ or $\|a\|_1$ or $\|a\|_2$

why? $\|a\|_\infty \leq \|a\|_2 \leq \|a\|_1 \leq (\dim)_{\mathcal{K}} \|a\|_\infty$

$a_n \to 0$ in $\|a\|$ or $\|a\|_1$ or $\|a\|_2$

why?

$$\boxed{\|a\|_\infty \le \|a\|_2 \le \|a\|_1 \le (\dim)_{\mathcal{H}} \|a\|_\infty}$$

* of course if we care about errors as in how close two density matrices are

$$\|\rho_1 - \rho_2\|_1 \le \varepsilon$$

then we also often care how ε scales with $(\dim_{\mathcal{H}})$ $\Rightarrow$ don't have norm equivilence

In ∞ dimensions we never have norm equiv.

$L(\mathcal{H}) \to B(\mathcal{H})$ where $\|a\| < \infty$

diff Topol:

$a_n \to a$ $\quad \|a_n - a\| \to 0$

$SO - a_n \to a$ $\quad \|(a_n - a)|\psi\rangle\| \to 0 \quad \forall \psi \in \mathcal{H}$

$WO - a_n \to a$ $\quad \langle\phi|a_n - a|\psi\rangle \to 0 \quad \forall \psi, \phi \in \mathcal{H}$

Norm $\Rightarrow$ SO $\Rightarrow$ WO But not other way around.

Von Neumann Algebra

$\mathcal{N} \subset B(\mathcal{H})$ subalgebra, closed

under $\mathcal{N} = \overline{\mathcal{N}}^{WO} = \overline{\mathcal{N}}^{SO}$

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Diff

SO - $a_n \to a$ $\quad \|(a_n - a)|\psi\rangle\| \to 0 \quad \forall \psi \in \mathcal{H}$

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$Z(\mathcal{N}) = \mathcal{N} \cap \mathcal{N}'$ always $= \mathbb{C}I$

Physics: • observables that can be approx

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Physics: • observables that can be approx in experiments $\mathcal{N} = \overline{\mathcal{N}}^{WO}$, assuming idealized setting

• states: $\rho : \mathcal{N} \to \mathbb{C}$, $\rho(a^{\dagger} a) \geq 0$

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Physics: • observables that can be approx in experiments $\mathcal{N} = \overline{\mathcal{N}}^{wo}$, assuming idealized setting

• states: $\rho : \mathcal{N} \to \mathbb{C}$, $\quad \rho(a^+ a) \geq 0$

$$\rho(1) = 1$$

$\rho \in \mathcal{N}_*$ continuous on ultraweak topol.

For $(B(\mathcal{H}))_* \to \operatorname{tr} \rho(\cdot)$ $\quad \|\rho\|_1 < \infty$

$$\operatorname{tr} \rho = 1, \quad \rho \geq 0$$

$(\mathcal{N})_* \ni \rho|_{\mathcal{N}}$ (like a partial trace)

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$(\mathcal{M})_* \ni \rho|_{\mathcal{M}}$ (like a partial trace)

In quantum gravity there are reasons to expect experiments are limited at finite G_N so we have to be especially careful about such seemingly technical things.

Also $\dim \mathcal{H}_{BH} \sim e^{(G_N)^{-1}}$ so again careful!!

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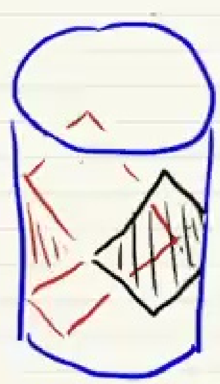
Concretely study these issues in AdS/CFT

$\rightsquigarrow$ YM theory SU(N) gauge thy.

- CFT_N $\quad G_N \propto 1/N^{\#}$ $\quad$ sequence $\mathcal{K}_N$



On cylinder: $\mathcal{K}$ $\quad N \in \mathbb{N}$

$O \mapsto M_N(O) \subset B(\mathcal{K}_N)$

AQFT $\quad O' = \{x \in \mathcal{K} : x \perp O\}$

$M_N(O)$ satisfies reasonable

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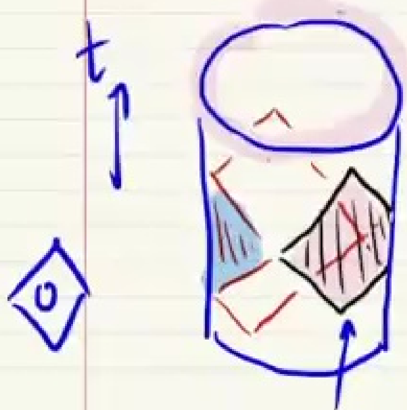

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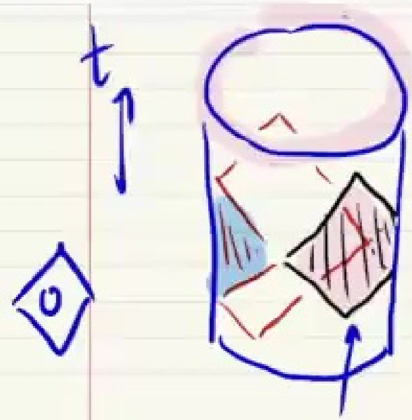
$M_N(O)$ satisfies reasonable conditions. Complete: $M_N(O') = M_N(O)'$

$\left(\text{compare to: } \mathcal{H}_{cyl} = \mathcal{H}_A \otimes \mathcal{H}_{\bar{A}} \right)$

Cover:

$O =$

Additive $\quad M_N(O) = \bigvee M_N(\diamond)$ locally



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Cover:

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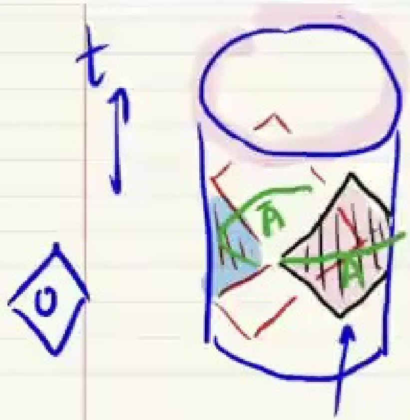
Additive $\quad M_N(O) = \bigvee_{\substack{\diamond \text{ cover} \\ \text{of } O}} M_N(\diamond)$ locally generated.

type III$_1$, hyperfinite factor

- Would like to model bulk in $N \to \infty$ limit



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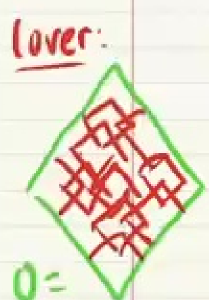

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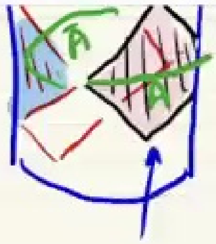

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  So semiclassical limit

$N = \infty$ theory is a theory of the single

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$\underline{N=\infty}$ theory is a theory of the single trace fields

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Say + $1/N$ pert. expansion.

formal pert. expansion $\mathbb{C}[1/N]$ ring.

Here: understand the $N=\infty$ theory first!

Use this to take the large-N limit.

$$\begin{array}{ccc} \infty\text{ dim} & & \infty\text{-dim} \\ \uparrow & & \uparrow \\ V_N : \mathcal{H} & \rightarrow & K_N \\ \nearrow & & \nearrow \\ \text{code} & & \text{physical} \end{array}$$

encoding map familiar from QEC

Same code for each N

$B(\mathcal{H})$ gen. by single trace fields

Use this to take the large-N limit.

∞ dim ∞-dim

$V_N : \mathcal{H} \to K_N$ encoding map familiar from QEC

Code Physical

Same code for each N

$B(x)$ gen. by single trace fields.

$C(O) \subset B(x)$ gen additively by single trace fields in O.

Bdry Label

$\gamma_N : C(O) \to M_N(O)$ simple reconstruction map

~ Extrapolate Dictionary

AIC

Together these satisfy:

$$\boxed{\begin{aligned} &\text{wo-}\lim_N \; V_N^\dagger V_N = 1 \\ &\text{so-}\lim_N \; \|(\gamma_N(c) V_N - V_N c)|\psi\rangle\| \to 0 \end{aligned}}$$

$\|V_N^\dagger V_N - 1\|_\infty \not\to 0$

Physical motivation: fix obs. / experiments

& states:

$$W_\psi = \langle\psi|\cdot|\psi\rangle \in B(\mathcal{H})_*$$

then for sufficiently small b_N expect code

to give good approx to this experiment.

(not allowed to change experiment with N)

Desired: from single trace fields

$W_\psi = \langle\psi|\cdot|\psi\rangle \in B(\mathcal{H})_*$

then for sufficiently small G_N expect code to give good approx to this experimnt.

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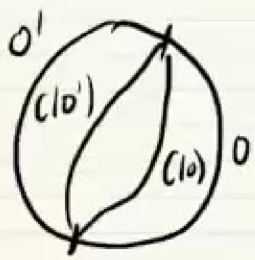
$\boxed{\text{Derived:}}$ from single trace fields following Liu, Leutheusser; Witten

$\underline{C(O)}$: non-trivial von Neumann algebra



Additive but not complete

i.e. $C(O) \subset C(O')'$

Haag dual violations.

Find

... for sufficiently small G_N expect ...

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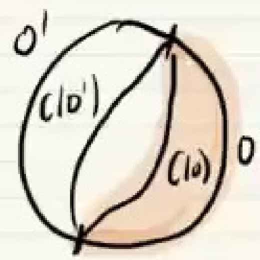

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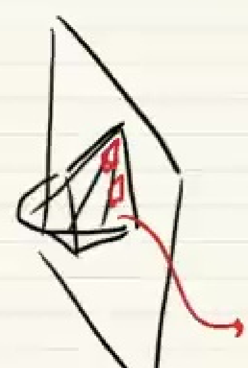
C(

fixed Background $G_N = 0$



C(O): causally complete bulk region

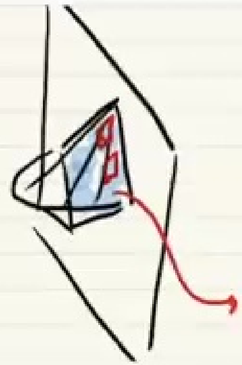
Additivity ... contained

$\underline{C(O)' = C(O')}$

fixed

Background

$G_N = 0$



$C(O)$: causally complete bulk region

Additivity gen: constrained by bulk causality

$C(O) =$ Causal completion of causal wedge $\boxed{J_+(O) \cap J_-(O)}$

~ HKLL, Modern: Time like Tube Theorem.

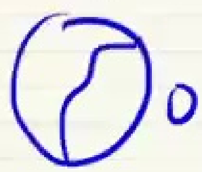
Entanglement Wedges:

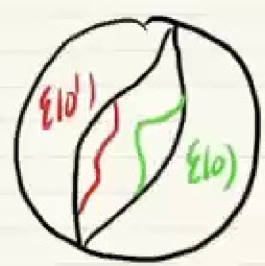
$C(O) =$ Causal completion of causal wedge

$$\boxed{J_+(O) \cap J_-(O)}$$

$\sim$ HKLL, Modern: Time like Tube Theorem.

Entanglement Wedges:





Extension of the causal wedge: $\boxed{\beta_N : \mathcal{E}(O) \to M_N(O)}$

s.t. $\text{so-}\,\beta_N(n) V_N - V_N n = 0 \quad \forall\, n \in \mathcal{E}(O)$

β_N: quantum channel, entanglement

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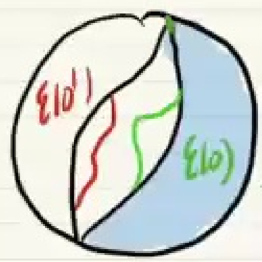
Entanglement Wedges:



O

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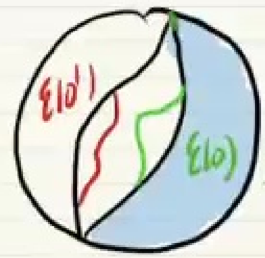
β_N: quantum channel, entanglement wedge reconstruction.

Theorem 1: Bulk maintains bdry causality

O'

Entanglement Wedges:



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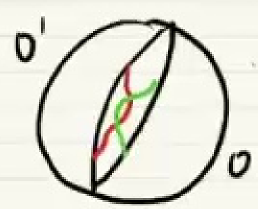
• 

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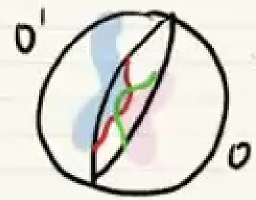
Theorem 1: bulk maintains bdry causality

• 

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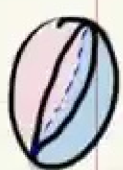


• i.e. $\boxed{\mathcal{E}(O) \subset \mathcal{E}(O')'}$ Einstein causality.

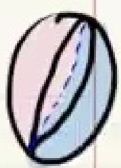
Theorem 2: Maximal extension (JLMS)

Equivalent conditions: $(1 \Leftrightarrow 2)$

1) $\boxed{\mathcal{E}(O) = \mathcal{E}(O')'}$ Entanglement wedge

2) "$\forall$" $\rho, \sigma \in B(\mathcal{H})$

$\lim S_{rel} (\rho_0 \mathrm{Adv}_{\ldots} \mid \sigma_0 \mathrm{Adv}_{\ldots} ; M_{\alpha}(O))$



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1) $\boxed{\mathcal{E}(O) = \mathcal{E}(O')'}$ Entanglement wedge

2) "$\forall$" $\rho, \sigma \in B(\mathcal{H})$

$$\lim_{N} S_{rel}\left(\rho \circ Ad V_N \,|\, \sigma \circ Ad V_N \,;\, M_N(O)\right)$$

$$= S_{rel}\left(\rho | \sigma \,;\, \mathcal{E}(O)\right)$$

Equiv. b/w QEC & Modular Flow Reconstruction

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Equiv. b/w QEC & Modular Flow Reconstruction

* New result: Assume $\exists\ \eta \in \mathcal{H}$ s.t.

jointly cyclic & sep for $\mathcal{C}(\upsilon)$ & $\mathcal{E}(\upsilon)$

$\overline{\mathcal{C}(\upsilon)|\eta\rangle} = \mathcal{H}$ $\quad c|\eta\rangle = 0 \Rightarrow 0$

$c = 0$

then we can add a 3rd condition to thm 2

3) $\displaystyle \text{so-}\lim_{N} \sigma_N^s(\gamma_N(c))V_N - V_N\sigma^s(c) = 0$

Modular Flow!

for $M_N(\upsilon); V_N\eta$ $\qquad$ for $\mathcal{E}(\upsilon); \eta$

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Modular Flow!

for $M_N(0); V_N \eta$ for $\mathcal{E}(0); \eta$

$\forall\ c \in \mathcal{C}(0)$

$\sigma^s_N(\cdot) = \rho_N^{is} (\cdot) \rho_N^{-is}$

Finite dimensions.

↳ Assumed in LM

How? Uses $\bigvee_{s \in \mathbb{R}} \sigma^s(\mathcal{C}(0)) = \mathcal{E}(0)$

Follows from joint cyclic & sep condition

Modular Flow!

for $M_N(0)$; $V_N\eta$ for $\mathcal{E}(0)$; η

$\sigma^{s(\cdot)}_N = \rho_N^{is} (\cdot) \rho_N^{-is}$

Finite dimensions.

$\forall c \in \mathcal{C}(0)$

Assumed in LM

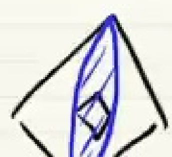
How? Uses $\forall_{s \in \mathbb{R}} \sigma^s(\mathcal{C}(0)) = \mathcal{E}(0)$

Follows from joint cyclic & sep. condition

Requires ∞ dims. Not in QFT

A kind of operator ergodicity

Also a simple time like tube thm:



CFT mod flow is geometric

Vacuum Codes: (still preliminary)

Interactions: $1/G_N$

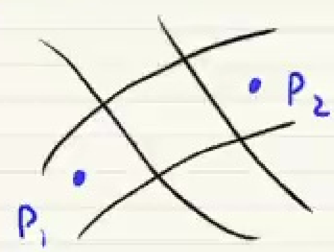
Quadratic: QFT fluctuations to fixed. $\mathcal{H}$

Classical soln to gravity in AdS b/c

fixed geometry

$G_N \to 0$

Phase space

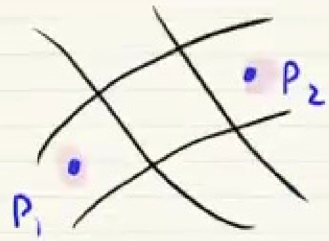


multiple codes

$V_N(p_i)$

Open: how to patch together ($1/N$)

Now: Study one particular code ... vacuum AdS



multiple codes

$V_N(p_i)$

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Now: Study one particular code p: vacuum AdS.

i.e. $\Omega_N \in K_N$ s.t.

$$|\Omega_N\rangle - V_N|\eta\rangle \to 0 \quad \text{some } \eta$$

bulk vacuum state

& K_N furnishes a unitary rep. of $SO(d,2)$ $V_N(g)$ acting w.r. on $M_N(0)$ & spectrum

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& K_N furnishes a unitary rep. of $SO(d,2)$ $V_N(g)$ acting cov. on $M_N(0)$ & spectrum condition:

$$H_{sd-1} \geq 0$$

Theorem (sketch):

Equivalent: $(1 \leftrightarrow 2)$

1) $\mathcal{E}(\lozenge) = \mathcal{C}(\lozenge)$ for diamonds

2) $\mathcal{H}$ furnishes a unitary rep of $SO(d,2)$ $U(g)$ acting cov. on $\mathcal{C}(0)$ w/ spectrum condition:

s.t.: $SO - U_N(g) V_N - V_N U(g) = 0$

$U|\eta\rangle = |\eta\rangle$

(2) $\mathcal{H}$ furnishes a unitary rep of $SO(d,2)$

$U(g)$ acting cov. on $C(O)$ w/ spectrum condition:

s.t. $\quad so - U_N(g)V_N - V_N U(g) = 0$

$U|\eta\rangle = |\eta\rangle$

Why? Since mod. theory for vacuum gives:

conformal boost.

combine to null translations

etc.

this is a simple form of bulk reconstruction:

isometries of AdS background.

How about a non-trivial entanglement wedge?

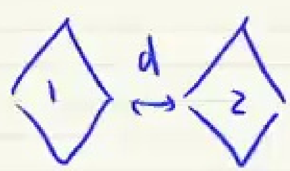
Theorem (sketch):

Assuming: $\boxed{\lim_{N} \mathrm{Tr}_{K_N}\, e^{-\beta H^{(N)}_{S^{d-1}}} = \mathrm{Tr}_{\mathcal{H}}\, e^{-\beta H_{S^{d-1}}}}$

$T < T_{HP}$ (e.g. Hawking Page)

then:

i) $\mathcal{E}(\Diamond_1 \vee \Diamond_2) = \mathcal{C}(\Diamond_1) \vee \mathcal{C}(\Diamond_2)$



for $d > \hbar / T_{HP}$

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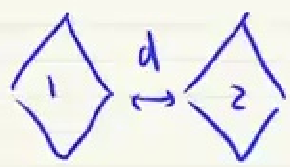


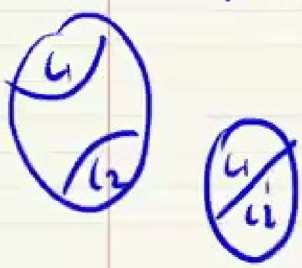
for $d > \hbar / T_{HP}$

ii) Bulk satisfies split property

i.e. $\exists\, S \subset \mathcal{K}$ s.t. $W_S(C_1 C_2) = W_{\mathcal{K}}(C_1)\, W_{\mathcal{K}}(C_2)$

for $d > \hbar / T_{HP}$

ii) Bulk satisfies split property

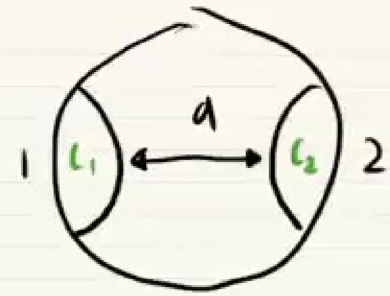


i.e. $\exists$ st X s.t. $\omega_s(C_1 C_2) = \omega_\eta(C_1)\,\omega_\eta(C_2)$

$\exists$ s.t. $\quad s_o\text{-}\lim_N \; |s_N\rangle - V_N|s\rangle = 0$

iii) $\quad \lim_N I(O_1 : O_2)_{V_N \psi} = I(O_1 : O_2)_\psi$

Expectations:



Bdry Split $\forall d$

Bulk Split

$\lim_N MI_N < \infty$

OUR THEOREM

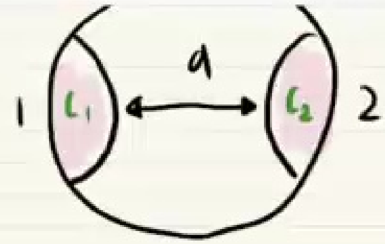
$1 \quad \ell_s \quad d_I \quad d_{HP} \quad d$

$\sim 1/T_{HP}$

Hagedorn Divergence in bulk. Condition for bulk

Mutual Information Transition

Expectations:



Bdry Split $\forall d$

Bulk Split

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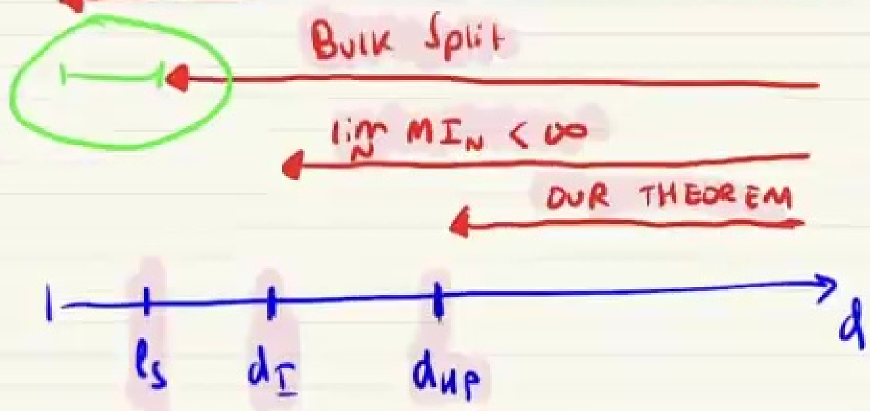
OUR THEOREM



$\sim 1/T_{HP}$

Hagedorn Divergence in bulk. Condition for bulk locality

Mutual Information Transition

9:41 AM Tue Jan 9 100%

Aic

Lec16 | Lec17 | Review-2 | Aic | Lec18 | max | Kids play | Lec19 | Lec20

Hayehorn

Divergence in

bulk. Condition

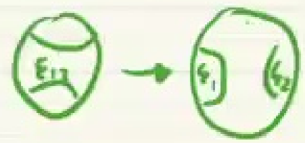
for bulk

locality

$\epsilon_s \to 0$

Mutual Information

Transition



$\epsilon_{12} = \epsilon_1 \vee \epsilon_2$

Thanks!