Quantum Error Correction For Gravitational Algebras @ large N

Tom Faulkner, University of Illinois Urbana Champaign

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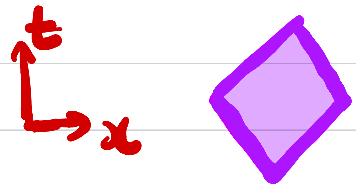
+ 2 Papers to appear

Gravitational Algebras:

In Algebraic Approach to QFT:



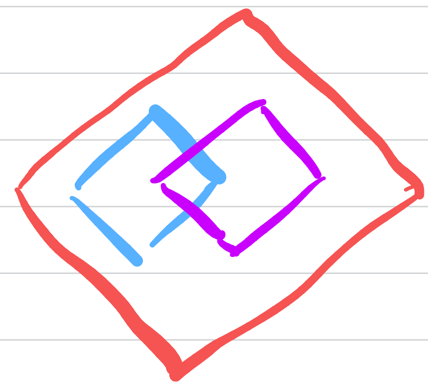
$\longrightarrow \quad \mathcal{A}(\diamond) \subset \mathcal{B}(\mathcal{H})$

Roughly ~ f(smeared local operators in $\diamond$)

+ Products & Sums

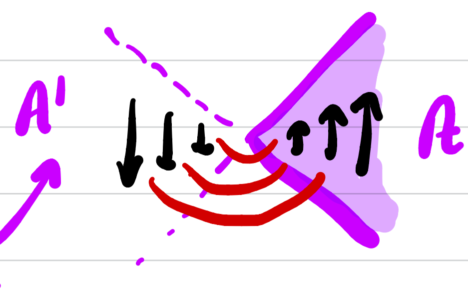
Axioms: Local nature of the QFT

(e.g. Haag Duality)



$\Rightarrow$ von Neumann Algebras, type III_1 factors

$\subset \text{Bounded}(\mathcal{H}_{QFT})$



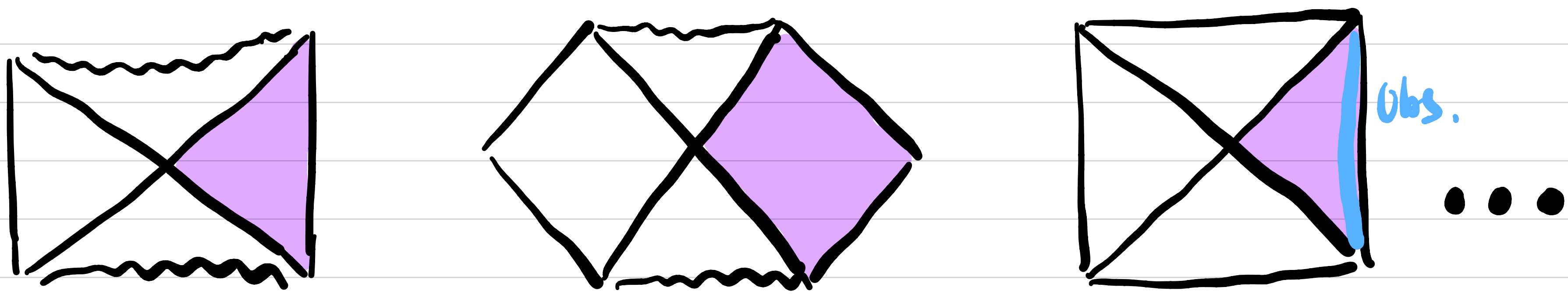
$A \cap A' = \text{trivial}$

Natural to wonder what happens in Quantum Grav.

Subtle: localized regions, diff. invariant, background independent.

Semiclassical limit: Progress; Liu, Leutheusser; CPLW, ...

Roughly: $G_N \to 0$, QFT + diffeo. constraints



AdS BH   Sch. BH   dS

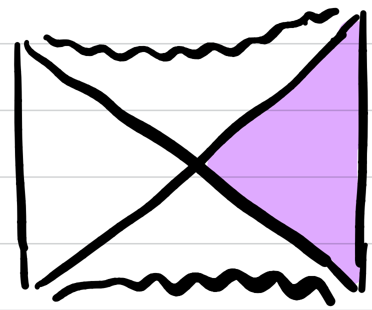
$\underbrace{\text{type III}_1}$ / $\underbrace{\text{type II}_\infty}$ $\leftarrow$ $\underbrace{\text{type II}_1}$

Different ∞ entanglement structure allowed.

Emergence of Geometry

$G_N \to 0$ Finite: N or G_N

AdS/CFT / Holography:



$$\to \sum_i e^{-\beta E_i} |E_i\rangle^* \otimes |E_i\rangle$$

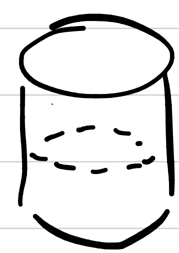
TFD $\in \mathcal{H}_L \otimes \mathcal{H}_R$ Right obs: $\mathbb{1}_L \otimes B(\mathcal{H}_R)$

type I_∞: $\exists$ Pure States

e.g. $|E_i\rangle\langle E_i|$

So type $I_\infty \xrightarrow[N\to\infty]{}$ type III_1 / II_∞

Large-N limit in AdS/CFT



$\mathcal{H}_N^R$

Sequence of theories $N \in \mathbb{N}$,

e.g.: $CFT^L_N \otimes CFT^R_N$ with $\mathcal{H}_N = \mathcal{H}^L_N \otimes \mathcal{H}^R_N$

on L, R CFTs

- $\phi^i_N = \mathrm{tr}_N(M_1 M_2 \ldots)$ Single trace fields
- $|\psi_N\rangle$ sequence of states $\in \mathcal{H}_N$ (e.g. $|TFD^N_\beta\rangle$)
- Correlation functions: $\phi^i_N \to \phi^i_N - \langle \phi^i_N \rangle_{\psi_N}$

$$\langle \phi^1_N \phi^2_N \phi^3_N \phi^4_N \rangle_{\psi_N} \xrightarrow[N\to\infty]{} \langle \phi^1_N \phi^2_N \rangle_{\psi_N} \langle \phi^3_N \phi^4_N \rangle_{\psi_N}$$

+ perms.

- Large N fields behave like GFFs

$\phi^i \equiv \phi^i_\infty$; abstract ops.

- $\mathcal{H}_{bulk} = \mathcal{H}_{GNS} \sim \phi^1 \phi^2 \ldots \phi^k |1\rangle$ / null states.

$$\langle 1 | (\tilde{\phi}^1 \ldots \tilde{\phi}^q)(\phi^1 \ldots \phi^k) | 1 \rangle = \lim_N \langle \tilde{\phi}^1_N \ldots \tilde{\phi}^q_N \phi^1_N \ldots \phi^k_N \rangle_{\psi_N}$$

Emergent von Neumann algebra: Liu, Leutheusser

$$\pi(\phi^1)\,\phi^2 \dots \phi^k |1\rangle = \phi^1 \phi^2 \dots \phi^k |1\rangle$$

$C(R)$ = closure alg. gen. $\pi(\phi^i)$

Right CFT

Supported on Right CFT

$\subset B(\mathcal{H}_{GNS})$

Type III_1: guaranteed by properties $\langle \phi^i \phi^j \rangle$

(E. Gesteau's talk)

type II ~ include H_{CFT}

Q1: How do we get back the type I_∞ algebra?

$\rightsquigarrow$ How do we see microstates?

Q2: type II algebras have entropies

$S_{\mathrm{II}}(\rho) + C$ defined using max. mixed state

what is C? what sense is:

$S_N(\rho_N) \to S_{\mathrm{II}}(\rho)$ true?

Q3: How does string theory fit in?

Today: construct a Quantum Error Correcting Code that attempts to address Q1-3

claim: natural extension of above discussion

$\underline{\text{QEC}}$: How does bulk theory fit into microscopics

(code) $\mathcal{H} = \mathcal{H}_{GNS}$ $\qquad$ $\boxed{K_N \text{ fixed } N}$ (physical)

Need.

$V_N : \mathcal{H} \to K_N$ $\qquad$ Sequence of maps.

$\underline{\text{Funny}}$: $\dim \mathcal{H} = \infty$ $\qquad$ $\dim K_N \sim e^{2S_N}$ finite

Construct as follows: $\gamma_N : \phi^i \to \phi^i_N$

γ_N gives the correct representative of

Single trace field $= \underset{N\times N}{\mathrm{Tr}} M_1 \cdots M_k$

Def. of large-N limit. $\qquad$ @ Fixed N

✓ GNS.

<u>Def:</u> $\gamma_N(\phi^i \ldots)|\Psi_N\rangle = V_N \pi(\phi^i \ldots)|1\rangle$

(technically V_N could be badly behaved, but possible to project $V_N \to V_N \Pi_N$ to fix)

<u>Then:</u> show $V_N^\dagger V_N \to \mathbb{I}_{\mathcal{H}}$ Pointwise!

$\forall$ matrix elements $\langle \xi_1 | \cdot | \xi_2 \rangle$ on $\mathcal{H}$

$$\langle \xi_1 | V_N^\dagger V_N | \xi_2 \rangle \to \langle \xi_1 | \xi_2 \rangle$$

<u>Key:</u> allows $V_N : \underset{\infty\text{-dim}}{\mathcal{H}} \to \underset{\text{finite dim}}{K_N}$ to work.

<u>Also:</u> in ∞ $\not\Rightarrow$ $\| V_N^\dagger V_N - \mathbb{I}_{\mathcal{H}} \| \to 0$

this would be uniform convergence.

Typical QEC $\quad V : \mathcal{H} \to K \quad \left.\begin{array}{l} V^\dagger V = \mathbb{1} \\ VV^\dagger = e \end{array}\right\}$ Isometry

Approximate QEC $\quad \| V^\dagger V - \mathbb{1} \| < \varepsilon$

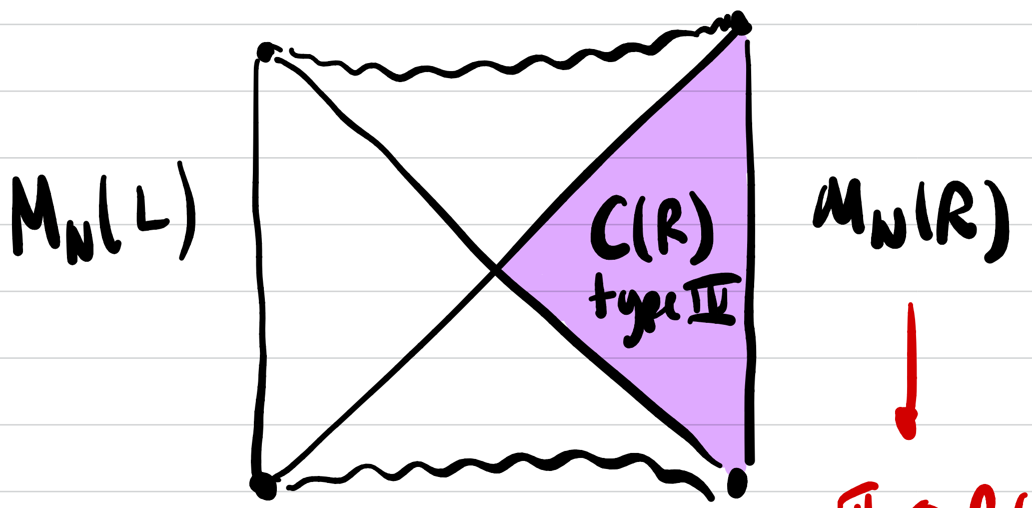
Here: "pointwise approximate QEC" $\longrightarrow$

"Asymptotically Isometric Codes" TF, Li

But does it work like other QEC codes?

YES!

Operator Reconstruction: (Dong, Harlow, Wall; Harlow)



$$\mathbb{I} \otimes B(K_N^R)$$
type-I

Defined by:

$$\beta_N^R(c_R) V_N - V_N c_R \to 0$$

pointwise sense.

$$\forall \; c_R \in C(R)$$

$$\beta_N^R : C(R) \to M_N(R)$$

Proved 2 main Theorems; Pointwise Approximate

1. Information Disturbance Tradeoff (no-cloning)

→ maintain bdry causality in bulk

$$\exists \; \beta_N^R \quad \leftrightarrow \quad [V_N^\dagger X_N^L V_N, C(R)] \to 0$$

2. Reconstruction wedges: gen $\mathcal{E}(L) \subset \mathcal{E}(R)'$

Largest algebras $\mathcal{E}(L), \mathcal{E}(R) \subset B(\mathcal{H})$

Reconstructed from $M_N(L), M_N(R) \subset B(K_N)$

Then

① Maximal Reconstruction

$$\mathcal{E}(L) = \mathcal{E}(R)'$$

all that commute with $\mathcal{E}(R)$

Haag Duality Bulk

② $S_{rel}(\psi_N | \phi_N ; M_N(R)) \to S(\psi | \phi ; \mathcal{E}(R))$

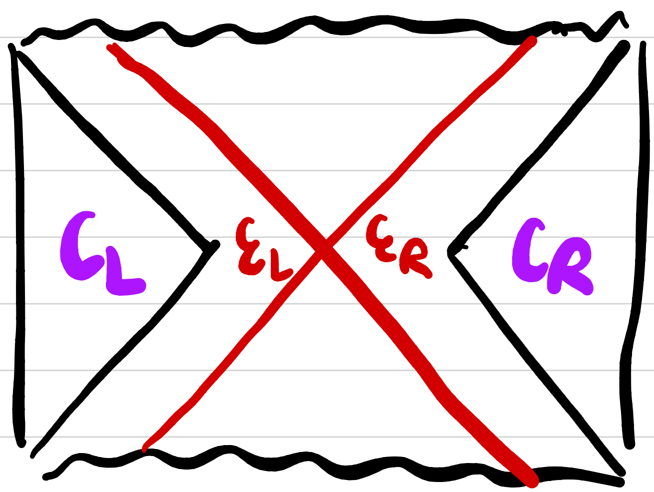
$\forall\, \psi, \phi \in \mathcal{H}$ & $\psi_N - V_N \psi \to 0 \quad \phi_N - V_N \phi \to 0$

③ $\Delta^{is}_{M_N(R)} V_N - V_N \Delta^{is}_{\mathcal{E}(R)} \to 0$

Δ^{is}: Tomita Takesaki Modular Op: $\rho^{is}_{N,L} \otimes \rho^{-is}_{N,R}$

Assumptions in 1, 2 trivially satisfied by BH case

More complicated settings:



C_L, C_R easy to reconstruct: use γ_N, $\equiv$ causal wedges

$\underline{Q}$: what conditions guarantees such maximal reconstructions?

$\mathcal{E}_L = \mathcal{E}_R'$ follows by HRT formula in many situations $\rightarrow$ Grav. Path Integral

WIP w/ Li

Entropy works as follows: if $\mathcal{E}(R) = \mathcal{E}(L)'$ type II_1 then:

$\exists$ $a_N \to \infty$ numbers s.t

$$\lim_{N\to\infty} \left(S_{vN}(\psi_N; M_N(R)) - a_N \right) = S_{\mathrm{II}}(\psi; C(R))$$

$\forall$ $\psi_N - V_N\psi \to 0$

(Modulo some extra assumptions on code & "smoothing" of S_{vN})

$\underline{\underline{a_N}}$: Give the unknown shift in the type-II entropy.

✓ one copy

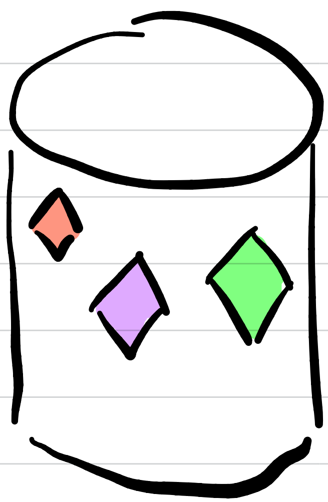
For vacuum codes: i.e. $K_N = K_N^{CFT}$ $\psi_N = \Omega_N$

Where $\mathcal{H}$ has a representation $U(g)$ of

$SO(d,2)$ CFT symm's.

s.t. $U_N(g)\, V_N - V_N\, U(g) \to 0$

Then:

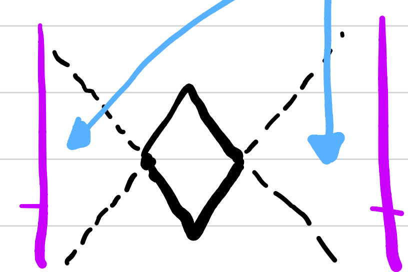


$M_N(\Diamond\text{'s})$ Bdy Algebras

$\downarrow$

$C(\Diamond)$ or $\mathcal{E}(\Diamond)' = \mathcal{E}(\Diamond')$

Without P.I what can we say?



Vacuum Codes: WIP

1. $\Diamond = \Diamond$ Double Cone then

$\mathcal{E}(\Diamond) = \mathcal{C}(\Diamond)$ uses algebraic version Bisognano Wichmann.

✓

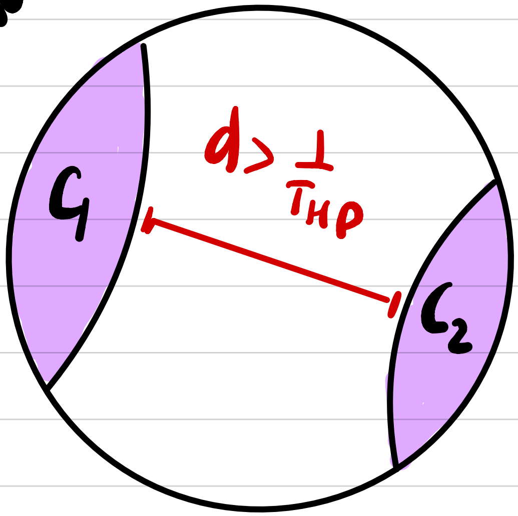
2. For two such regions $\Diamond_1 \cup \Diamond_2$

then, prove: $\mathcal{E}(\Diamond_1 \cup \Diamond_2) = \mathcal{C}(\Diamond_1 \cup \Diamond_2)$

if diamonds are sufficiently separated $d > d_c$

with $\mathrm{Tr}_{\mathcal{K}_N} e^{-\beta H_N} \to \mathrm{Tr}_{\mathcal{H}} e^{-\beta H}$ $\forall$ $T < 1/d_c = T_{HP}$

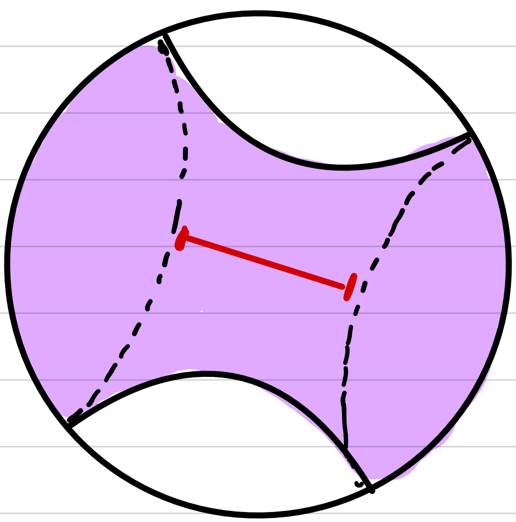
Slice AdS:



d: exactly the minimal geodesic distance b/w minimal surfaces C_1, C_2

Non-trivial dynamical statement

Note: $d_{HP} > d_{MI}$ so more work required to reproduce AdS/CFT predictions



Proof of this fact use same ideas relating split property to thermodynamics.

Longo et al.

Hagedorn Divergence in Bulk Theory

$$\mathrm{Tr}_{\mathcal{H}}\, e^{-\beta H} = \infty$$

$$T > T_{Hag}$$

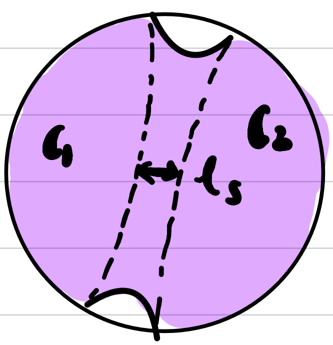
$N=4$ SYM at finite λ

→ order of limits: $\lim_{T \to T_{Hag}} \lim_{N \to \infty}$

Plausibly Leads To Violations of the Split Property:

(Split: $C_1 \vee C_2 \cong C_1 \otimes C_2$)

For $d < 1/T_{Hag} \sim 1/\lambda^{1/4}$



Can be detected using the code.

Thank You!