Title: The Quantum Null Energy Condition from Causality

Date: Jul 31, 2017 01:00 PM

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Abstract: <p>IT from Qubit web seminar</p>

THE QUANTUM NULL ENERGY CONDITION FROM CAUSALITY

based on arXiv: **1706.09432** with:

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Tom Faulkner
University of Illinois at Urbana-Champaign

qnec-talk (page 2 of 94) — Edited

OUTLINE

Warnings:
$2\pi = 1$

- motivational QNEC
- proving the ANEC in two ways
- introduce $f(s)$ and properties thereof
- whence $f(s)$? causality of entangling surfaces in AdS/CFT
- calculation (modular flow using defect OPE)
- generalizations and conclusions

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THE QNEC

some local negative energy density

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THE QNEC

- Globally, energy in QFT is positive (above ground state), but local energy density can be negative

- Classical field theory, Null Energy Condition (NEC):

$$T_{uu}(y) \sim (\partial_u \phi)^2 \geq 0 \qquad u = \text{light-like coordinate}$$

- Quantum mechanics: violated by quantum fluctuations, but:

$$\langle T_{uu}(y) \rangle_\psi \geq D_u^2 S_{EE}(A) \qquad y \in \partial A$$

Bousso, Fisher, (Koeller), Leichenauer, Wall `15

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THE QNEC

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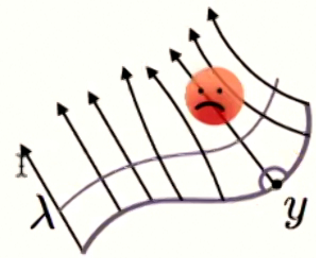
MOTIVATION I - LEARNING ABOUT QFT FROM GENERAL RELATIVITY

- gravity focuses light rays (does not anti-focus)

- Raychaudhuri's equation:

$$\frac{d\theta}{d\lambda} = -\theta^2 - \sigma^2 - G_N T_{uu} \leq 0$$

$$\theta \sim \mathcal{K}_u \sim \frac{\delta \text{Area}}{\delta x^u(y)}$$



- But violated in quantum (semi-classical) gravity?

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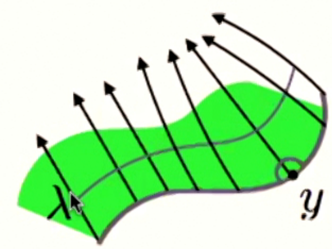
MOTIVATION I - LEARNING ABOUT QFT FROM GENERAL RELATIVITY

- Area ~ entropy ⟶ generalized entropy

$$S_{\text{gen}} = S_{EE}(A) + \frac{\text{Area}(\partial A)}{4G_N}$$



- Leads to quantum focusing conjecture (QFC):

$$\Theta = \frac{\delta}{\delta x^u(y)}\left(\text{Area} + 4G_N S_{EE}\right) \qquad \frac{d\Theta(A;y)}{d\lambda} \leq 0$$

- QNEC follows from flat space limit:

$$\theta = 0 \quad \sigma = 0$$

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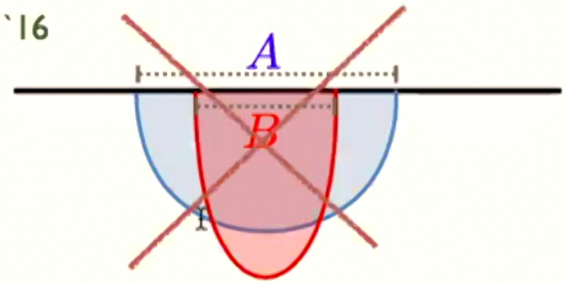
MOTIVATION II - BULK CAUSALITY AND ADS/CFT

- In AdS/CFT the QNEC follows from causal properties of the HRT surface: Koeller, Leichenauer, `16



- Entanglement Wedge Nesting

$$B \subset A \qquad \mathcal{E}_B \subset \mathcal{E}_A$$

- Links many different areas of study: bulk reconstruction

entanglement

modular Hamiltonians

chaos bound

ANEC

micro causality and the bootstrap

emergence of bulk locality from QFT??

defect CFTs

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REMINDERS

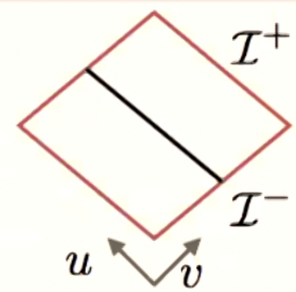
- The QNEC is a conjectured property of QFTs (no gravity)
- We will prove it in Minkowski space, although proof should extend to QFTs in curved space
- We will work with general QFTs with an interacting UV fixed point and d>2
- We start our story with the ANEC …

TWO PATHS TO THE ANEC

THE ANEC

- The averaged NEC:

$$\mathcal{A}_u = \int_{-\infty}^{\infty} du' \, \langle T_{uu}(u', v' = 0, y) \rangle_\psi \geq 0$$



- Also predicted from GR (e.g. by demanding wormholes not traversable)

- Non trivial in Minkowski space ~ Hofman-Maldacena bounds

In d=4 CFTs: $\frac{31}{18} \geq \frac{a}{c} \geq \frac{1}{3}$

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METHOD I: MODULAR HAMILTONIANS

TF, Leigh, Parrikar, Wang, `16

$$\mathcal{H}_{tot} = \mathcal{H}_A \otimes \mathcal{H}_{\bar{A}} \qquad \rho_A = \mathrm{Tr}_{\bar{A}} \left|\psi\right\rangle \left\langle\psi\right|$$

$$H_A = -\ln \rho_A$$

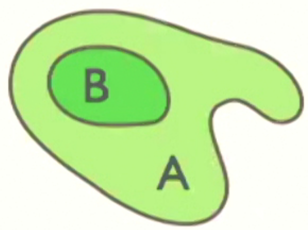
"Full" Modular Hamiltonian - better behaved in QFT:

$$K_A = H_A \otimes 1_{\bar{A}} - 1_A \otimes H_{\bar{A}}$$

Inclusion property:

$$B \subset A$$

$$K_A - K_B \geq 0$$



Proof: relative entropy monotonicity

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MODULAR HAMILTONIANS

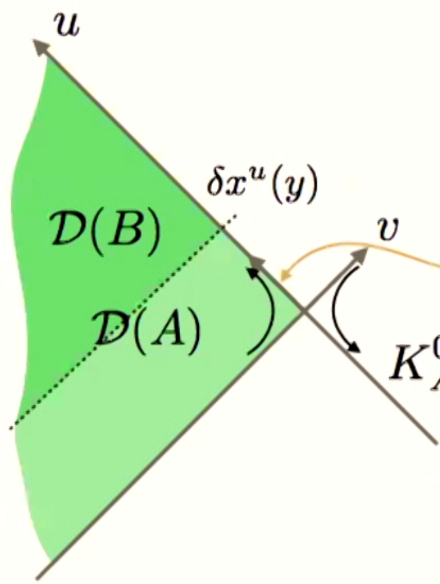
Relativistic QFT - inclusion at level of causal domains

specialize to vacuum state: $|\psi\rangle \rightarrow |0\rangle$

A: half space (Rindler) cut

$K_A^0 =$ Boost operator

B: small null deformation thereof



$$K_A^0 - K_B^0 = \int dy \int_{-\infty}^{\infty} du' \delta x^u(y) T_{uu}(u')$$

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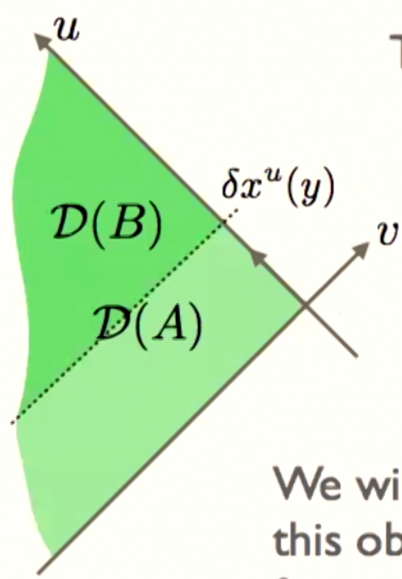
MODULAR HAMILTONIANS



Our approach was perturbative in $\delta x^u(y)$

Turns out this is an exact result — Lashkari `17; Casini, Teste, Torroba `17

$$\Longrightarrow \quad [K_B^0, K_A^0] = i(K_A^0 - K_B^0)$$

Only true for vacuum:
"Half-Sided Modular Inclusions"

$$e^{-iK_B^0 s} e^{iK_A^0 s} = e^{i(1-e^{-s})P_u}$$

gens null "translations"

$$P_u = K_B^0 - K_A^0$$

We will be studying this object a lot, but for non vacuum states!

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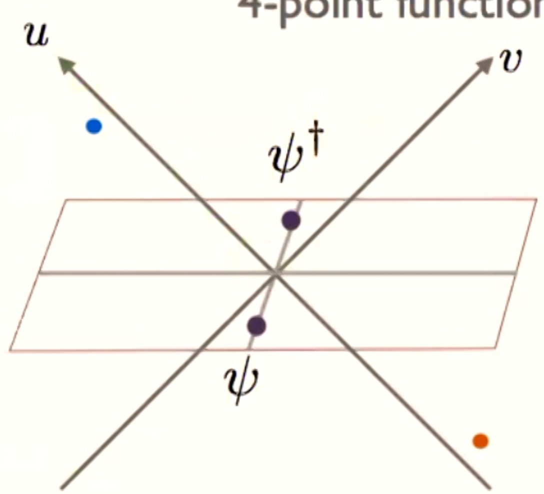
METHOD II: CAUSALITY

Hartman, Kundu, Tajdini `16

$$f(u) \propto \langle\psi|\,\mathcal{O}(u,v)\mathcal{O}(-u,-v)\,|\psi\rangle$$

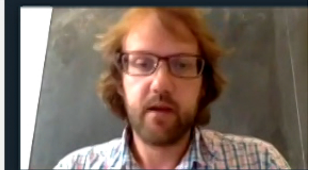
4-point function - conformal bootstrap



$$\langle\psi|\,[\mathcal{O},\mathcal{O}]\,|\psi\rangle = 0$$

Causality: space-like separated

$f(u)$ analytic in u, v



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COMPUTABLE: LIGHTCONE OPE

$$f(u) \propto \langle\psi|\, \mathcal{O}(u,v)\mathcal{O}(-u,-v)\, |\psi\rangle$$

$$\frac{\mathcal{O}(u,v)\mathcal{O}(-u,-v)}{\langle\mathcal{O}(u,v)\mathcal{O}(-u,-v)\rangle} \sim \sum_k u^{(\Delta_k+\ell_k)/2} v^{(\Delta_k-\ell_k)/2} \mathcal{O}_k(0)$$

	KINEMATICS	DOMINANT OPS.	EXAMPLE
Euclidean OPE:	$u \sim v$	lowest dimension Δ	$\mathcal{O}_{\text{primary}}$
Lightcone OPE:	$v \ll u$	lowest twist $\tau = \Delta - \ell$	T_{uu} $\tau = d-2$, $\ell = 2$

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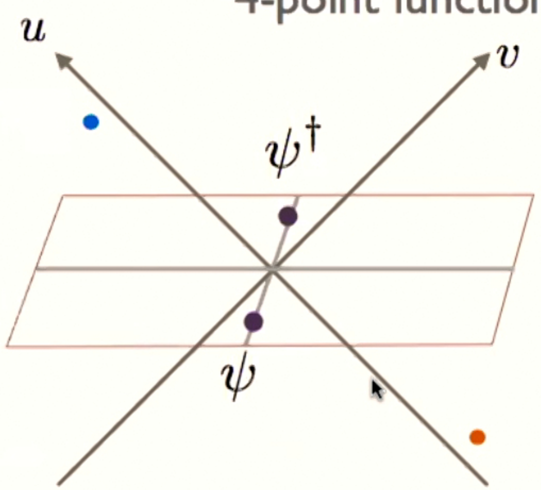
METHOD II: CAUSALITY

Hartman, Kundu, Tajdini `16

$$f(u) \propto \langle\psi|\,\mathcal{O}(u,v)\mathcal{O}(-u,-v)\,|\psi\rangle$$

4-point function - conformal bootstrap



$$\langle\psi|\,[\mathcal{O},\mathcal{O}]\,|\psi\rangle = 0$$

Causality: space-like separated

$f(u)$ analytic in u, v

Computability: in certain limits

Positivity: bound f(u) generally

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COMPUTABLE: LIGHTCONE OPE

$$f(u) \propto \langle\psi|\, \mathcal{O}(u,v)\mathcal{O}(-u,-v)\, |\psi\rangle$$

$$\frac{\mathcal{O}(u,v)\mathcal{O}(-u,-v)}{\langle\mathcal{O}(u,v)\mathcal{O}(-u,-v)\rangle} \sim \sum_k u^{(\Delta_k+\ell_k)/2} v^{(\Delta_k-\ell_k)/2} \mathcal{O}_k(0)$$

	KINEMATICS	DOMINANT OPS.	EXAMPLE
Euclidean OPE:	$u \sim v$	lowest dimension Δ	$\mathcal{O}_{\text{primary}}$
Lightcone OPE:	$v \ll u$	lowest twist $\tau = \Delta - \ell$	T_{uu} $\tau = d-2$, $\ell = 2$

But also: $\partial_u^{\ell-2} T_{uu} \quad \ell \geq 2$

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COMPUTABLE: LIGHTCONE OPE

Computable in the light cone limit: $v \to 0$ $u =$ fixed and somewhat large

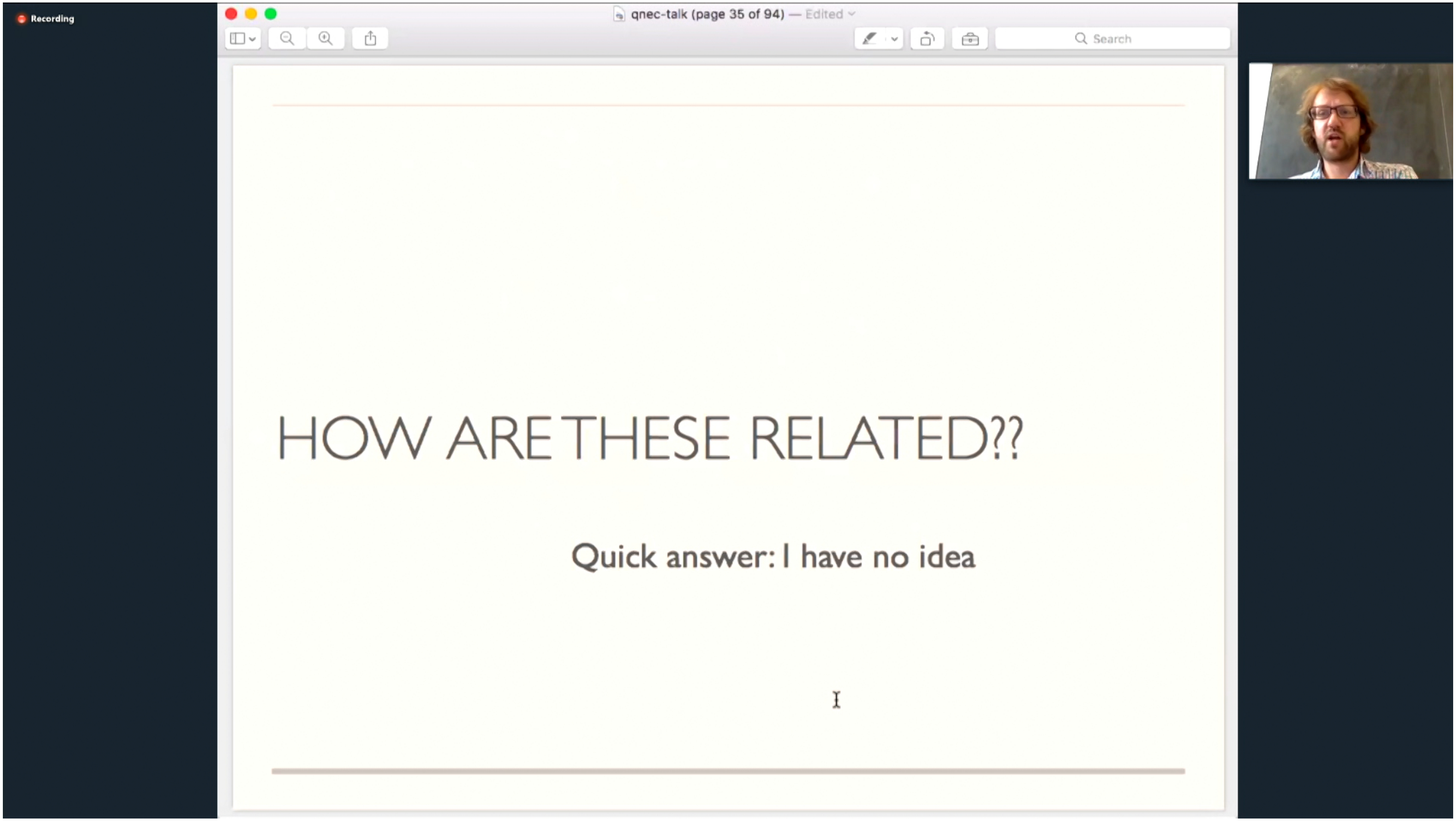
Re-sum $\partial_u^{\ell-2} T_{uu}(0)$ into an integral:

$$f = 1 - C_T^{-1}(-uv)^{\tau/2} u \mathcal{A}_u + \ldots$$

$$\mathcal{A}_u = \int_{-\infty}^{\infty} \langle T_{uu}(u', v=0) \rangle_\psi \, du'$$

Analyticity relates $\mathcal{A}_u$ to $f(u)$ in a range where it cannot be computed but it can be bounded (Wedge reflection positivity)

Hartman, Kundu, Tajdini \`16 $\mathcal{A}_u \geq 0$ Casini \`11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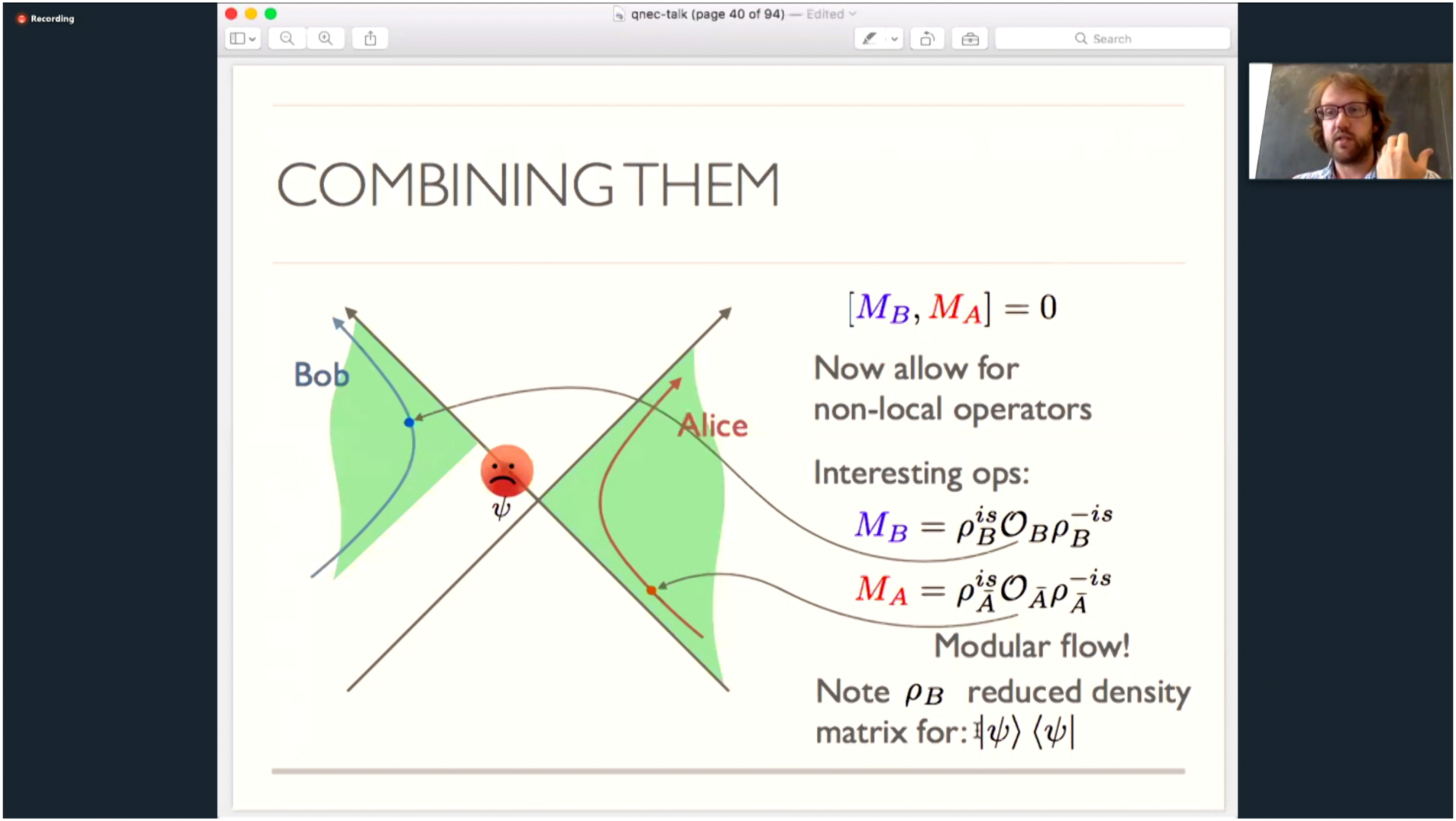
HOW ARE THESE RELATED??
Quick answer: I have no idea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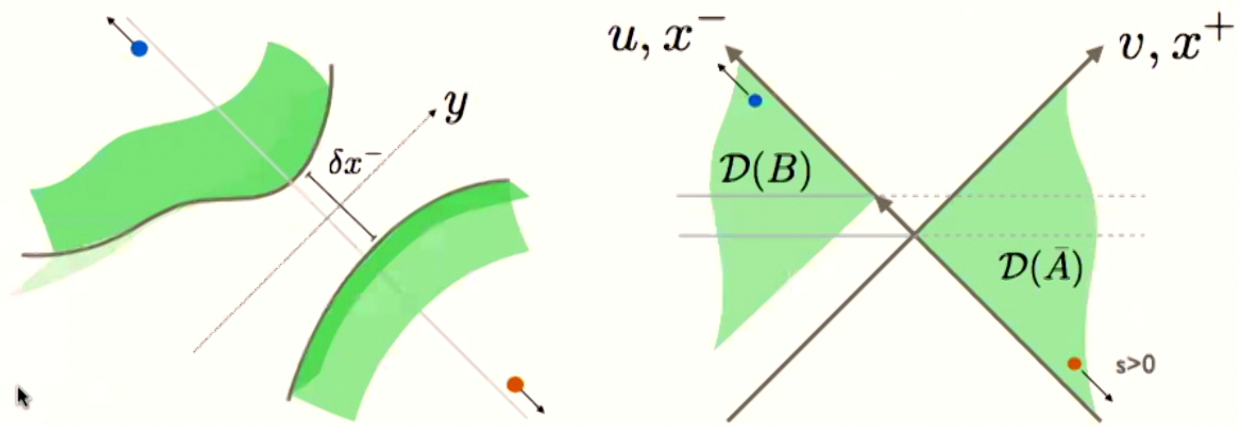
COMBINING THEM
Bob
Alice
ψ
$[M_B, M_A] = 0$
Now allow for
non-local operators
Interesting ops:
$M_B = \rho_B^{is} \mathcal{O}_B \rho_B^{-is}$
$M_A = \rho_{\bar{A}}^{is} \mathcal{O}_{\bar{A}} \rho_{\bar{A}}^{-is}$
Modular flow!
Note ρ_B reduced density
matrix for: $|\psi\rangle \langle\psi|$

SETUP



Main object of study:

$$f(s) \equiv \frac{\langle\psi|\,\mathcal{O}_B e^{-iK_B s} e^{iK_A s} \mathcal{O}_{\bar{A}}\,|\psi\rangle}{\langle\Omega|\,\mathcal{O}_B e^{-iK_B^0 s} e^{iK_A^0 s} \mathcal{O}_{\bar{A}}\,|\Omega\rangle}$$

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COMMENTS $f(s) \equiv \frac{\langle\psi|\, \mathcal{O}_B e^{-iK_B s} e^{iK_A s} \mathcal{O}_{\bar{A}} \,|\psi\rangle}{\langle\Omega|\, \mathcal{O}_B e^{-iK_B^0 s} e^{iK_A^0 s} \mathcal{O}_{\bar{A}} \,|\Omega\rangle}$

- The full modular Hamiltonian annihilates: $K_A |\psi\rangle = 0$

$$e^{iK_A s} \mathcal{O}_{\bar{A}} e^{-iK_A s} |\psi\rangle = \rho_{\bar{A}}^{is} \mathcal{O}_{\bar{A}} \rho_{\bar{A}}^{-is} |\psi\rangle$$

(recall $K_A = -\ln \rho_A + \ln \rho_{\bar{A}}$)

- Normalized with respect to vacuum modular flow

$$e^{-iK_B^0 s} e^{iK_A^0 s} = e^{i(1-e^{-s})P_-^0}$$

- We will now study properties of $f(s)$

- Very similar to ANEC $f(u)$ with $u \sim e^s$

see also: Bound on Chaos $f(t)$

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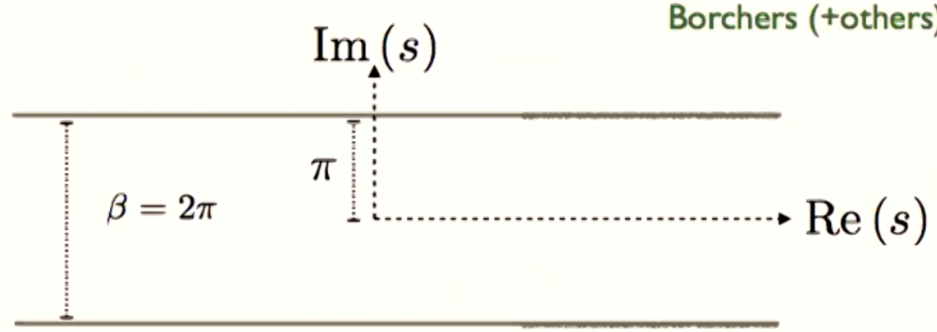
PROPERTIES: $f(s) \equiv \frac{\langle\psi| \mathcal{O}_B e^{-iK_B s} e^{iK_A s} \mathcal{O}_{\bar{A}} |\psi\rangle}{\langle\Omega| \mathcal{O}_B e^{-iK_B^0 s} e^{iK_A^0 s} \mathcal{O}_{\bar{A}} |\Omega\rangle}$

- **Causality:** modular flow ~ thermal time for non-equilibrium states ~ analog KMS condition ~ analyticity in the thermal strip:

Borchers (+others)



- Requires "nice states" (cyclic and separating) ~ large entanglement ~ all reasonable states in QFT (without firewalls)

PROPERTIES: $f(s) \equiv \dfrac{\langle\psi|\, \mathcal{O}_B e^{-iK_B s} e^{iK_A s} \mathcal{O}_{\bar{A}} \,|\psi\rangle}{\langle\Omega|\, \mathcal{O}_B e^{-iK_B^0 s} e^{iK_A^0 s} \mathcal{O}_{\bar{A}} \,|\Omega\rangle}$

- **Computability:** working in same ANEC light-cone limit for the operator insertions: $(\pm u, \pm v) \qquad v \to 0,\ u = \text{fixed}$

$$f(s) = 1 - C_T^{-1} e^s u (-uv)^{\frac{d-2}{2}} \mathcal{Q}_u + \dots \qquad s \gg 1\,(\text{fixed})$$

$$\mathcal{Q}_u = \int_{\partial A}^{\partial B} du' T_{uu}(u', v' = 0, y) + \left(\frac{\delta S_{EE}(\rho_A)}{\delta X^u(y)} - \frac{\delta S_{EE}(\rho_B)}{\delta X^u(y)} \right)$$

- Computed using a defect OPE (later)

  Modular flow ~ vacuum mod flow for ops light like separated from entangling surface

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PROPERTIES: $f(s) \equiv \dfrac{\langle\psi|\, \mathcal{O}_B e^{-iK_B s} e^{iK_A s} \mathcal{O}_{\bar{A}}\, |\psi\rangle}{\langle\Omega|\, \mathcal{O}_B e^{-iK_B^0 s} e^{iK_A^0 s} \mathcal{O}_{\bar{A}}\, |\Omega\rangle}$

- **Positivity:** use Cauchy-Schwarz to bound

$$|\langle b|\, a\rangle|^2 \leq \langle a|\, a\rangle \langle b|\, b\rangle$$

$$\mathrm{Re} f(s) < 1$$

$$\mathrm{Im} s = \pm\pi/2$$

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PROPERTIES:

$$f(s) \equiv \frac{\langle\psi|\, \mathcal{O}_B e^{-iK_B s} e^{iK_A s} \mathcal{O}_{\bar{A}} \,|\psi\rangle}{\langle\Omega|\, \mathcal{O}_B e^{-iK_B^0 s} e^{iK_A^0 s} \mathcal{O}_{\bar{A}} \,|\Omega\rangle}$$

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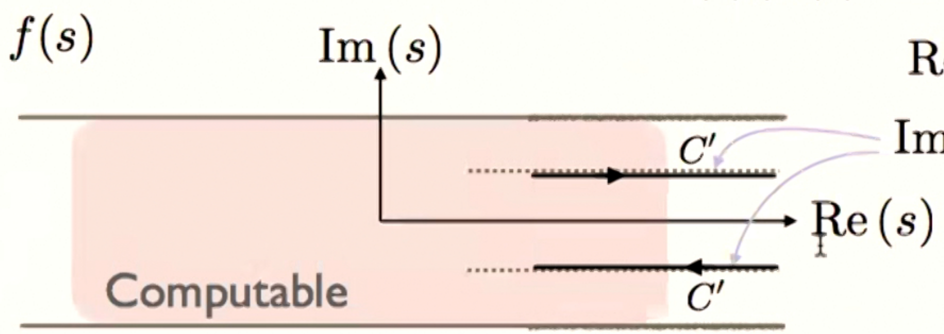
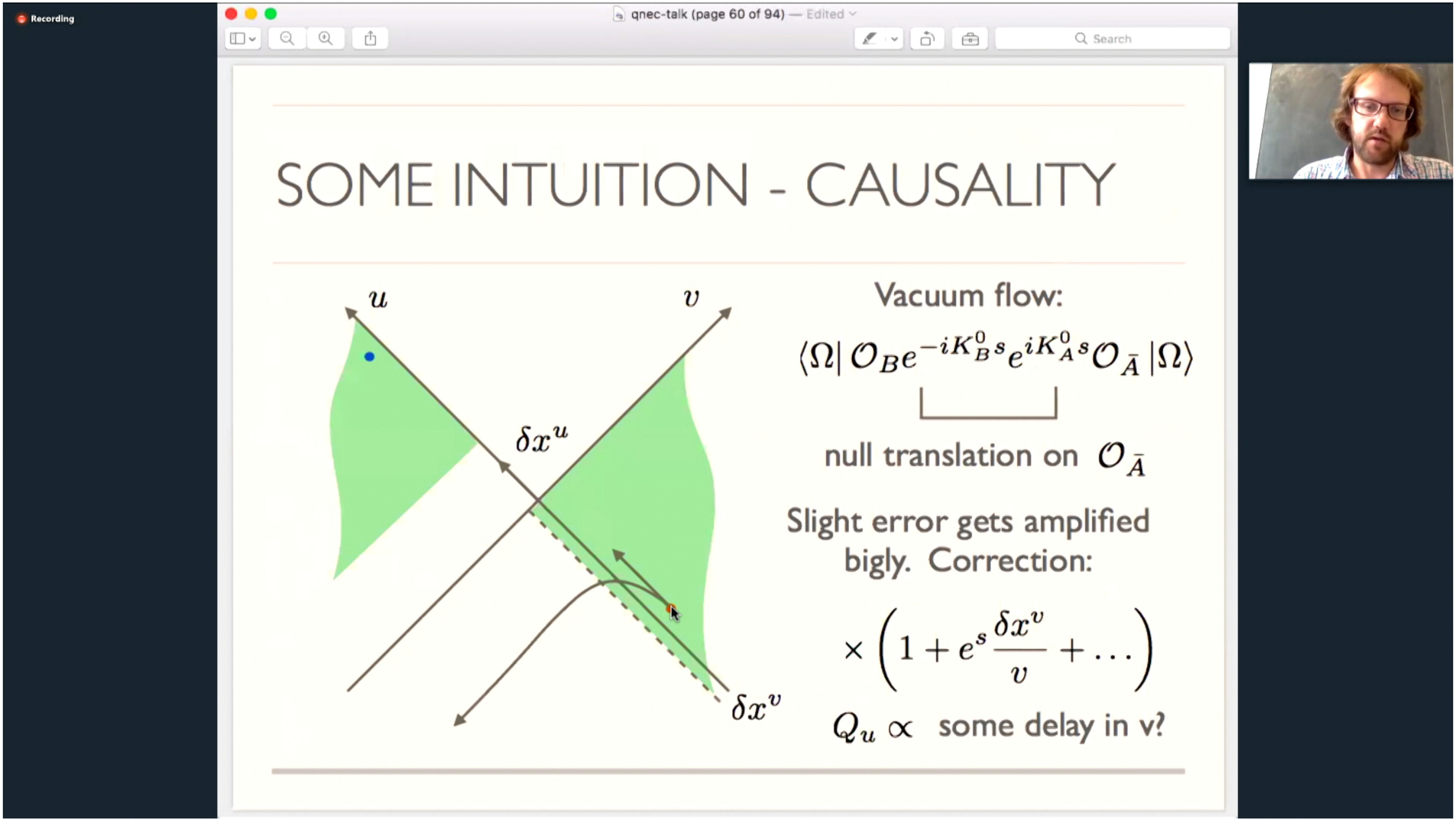


$$Q_u = \#\mathrm{Re}\left(i \int_{C'} ds e^{-s}(1 - f(s))\right) \geq 0$$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SOME INTUITION - CAUSALITY
u
v
δx^u
δx^v
Vacuum flow:
$\langle\Omega|\, \mathcal{O}_B e^{-iK_B^0 s} e^{iK_A^0 s} \mathcal{O}_{\bar{A}}\, |\Omega\rangle$
null translation on $\mathcal{O}_{\bar{A}}$
Slight error gets amplified bigly. Correction:
$\times \left(1 + e^s \frac{\delta x^v}{v} + \ldots\right)$
$Q_u \propto$ some delay in v?

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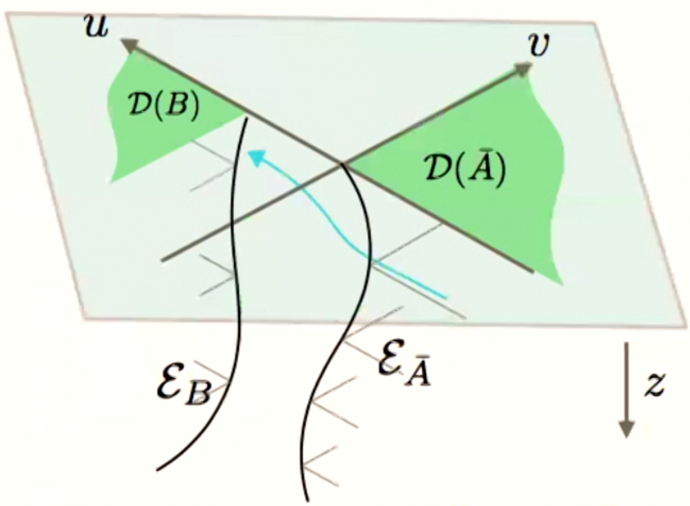
MORE INTUITION - ADS/CFT

Koeller, Leichenauer, `16



RT/HRT surfaces

Jafferis et al.
Lewkowycz TF
Cotler et al.

- Entanglement wedge nesting:

$$[\mathcal{D}(B), \mathcal{D}(\bar{A})] = 0$$

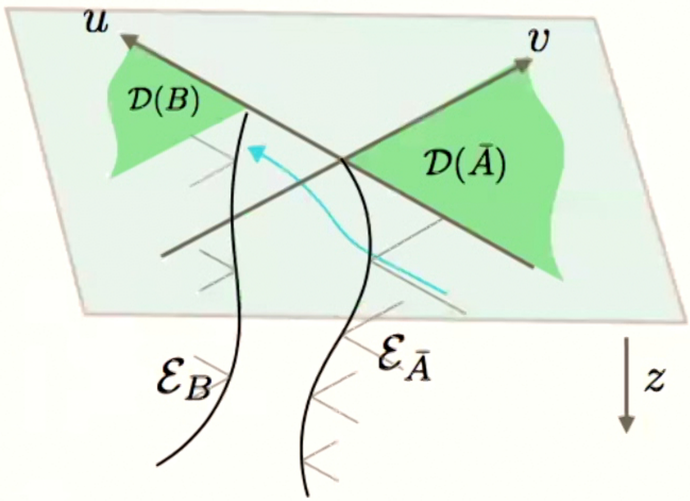
$$\implies [\mathcal{E}_B, \mathcal{E}_{\bar{A}}] = 0$$

- Try to send a null geodesic between them. Figure of merit:

$$\Delta v \propto -Q_u$$

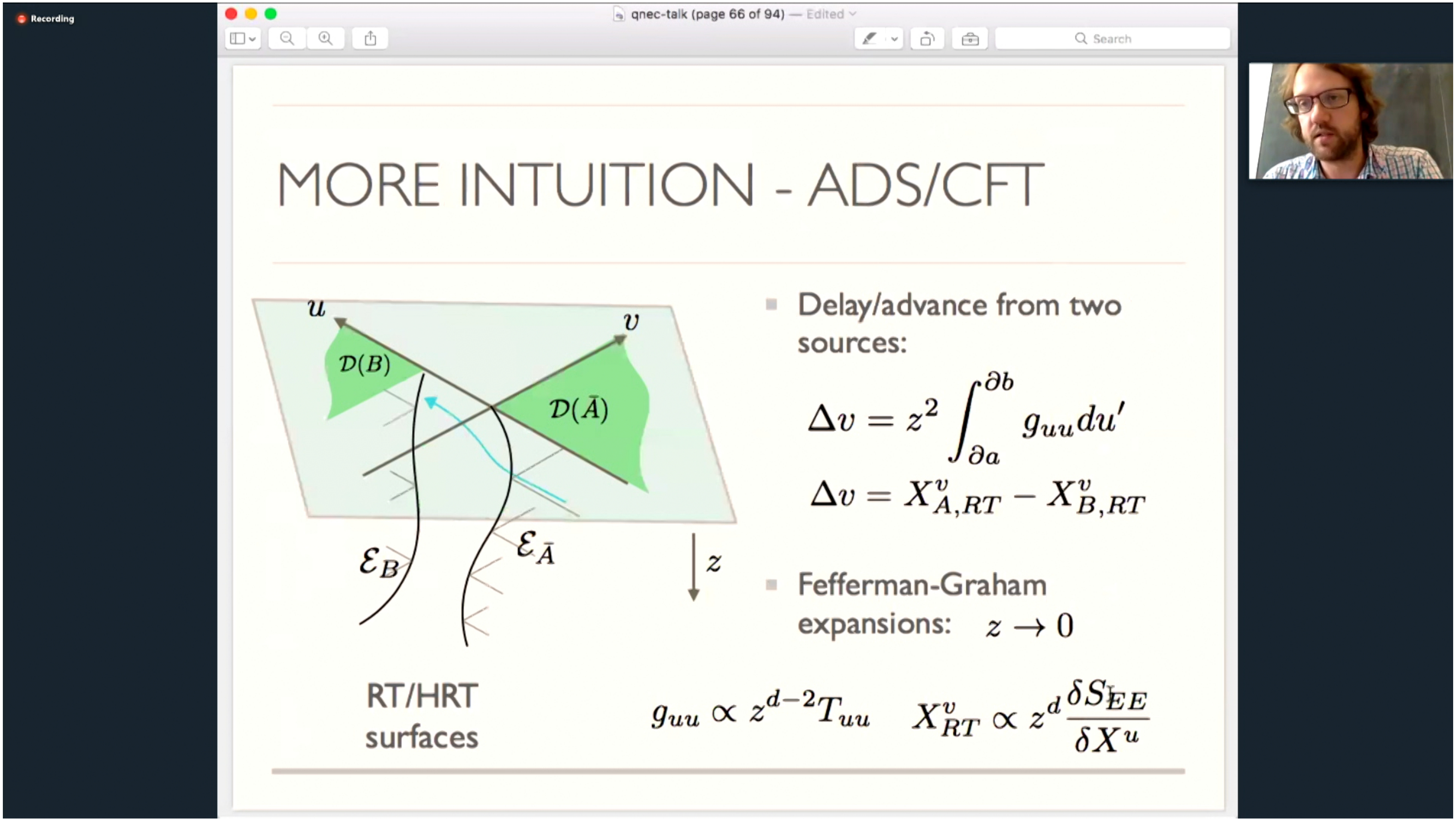
- Entanglement wedge reconstruction ~ related to modular flow

MORE INTUITION - ADS/CFT



RT/HRT surfaces

- Delay/advance from two sources: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MORE INTUITION - ADS/CFT
u
v
$\mathcal{D}(B)$
$\mathcal{D}(\bar{A})$
$\mathcal{E}_B$
$\mathcal{E}_{\bar{A}}$
z
RT/HRT surfaces
Delay/advance from two sources:
$\Delta v = z^2 \int_{\partial a}^{\partial b} g_{uu} du'$
$\Delta v = X^v_{A,RT} - X^v_{B,RT}$
Fefferman-Graham expansions: $z \to 0$
$g_{uu} \propto z^{d-2} T_{uu}$
$X^v_{RT} \propto z^d \frac{\delta S_{EE}}{\delta X^u}$

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THE COMPUTATION

"You can't compute that …"

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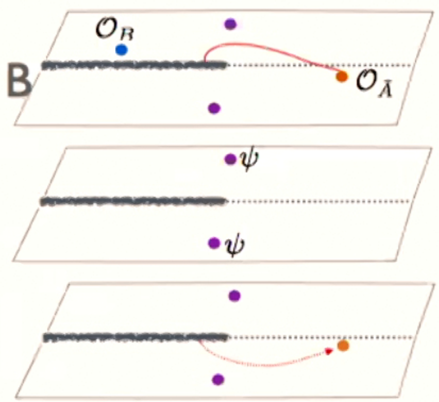
REPLICA TRICK

Simpler problem:
$\langle\psi|\, \mathcal{O}_B K_B \mathcal{O}_{\bar{A}}\, |\psi\rangle$



- Modular Hamiltonian:

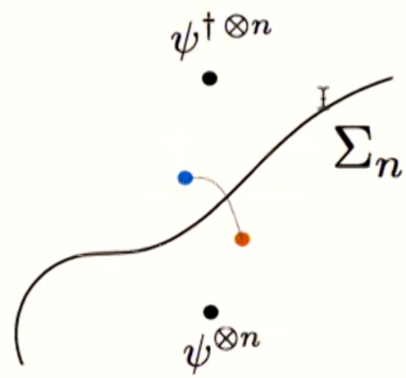
$$\lim_{n\to 1} \partial_n \rho_B^{n-1} = \ln \rho_B$$

- Path integral on n-replicated space
$\mathcal{M}_n \quad n \in \mathbb{Z}$
- n insertions of: $\psi, \psi^\dagger$
- matrix elements with $\mathcal{O}_B, \mathcal{O}_{\bar{A}}$
- 2n+2 correlation function on $\mathcal{M}_n$

Compute $\ln\rho_B - \ln\rho_{\bar{B}}$ via simple operator monodromy

ORBIFOLD THEORY

- Alternatively view as orbifold computation: $\mathrm{CFT}^n/\mathbb{Z}_n$



- only one stress tensor
- operators single valued
- but $\mathcal{O}_B, \mathcal{O}_{\bar{A}}$ not orbifold ops.

- Twist defect on entangling surface ~ co-dimension 2 operator

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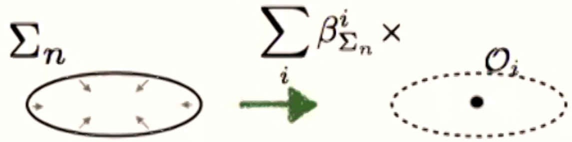
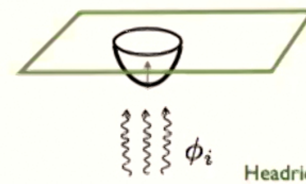
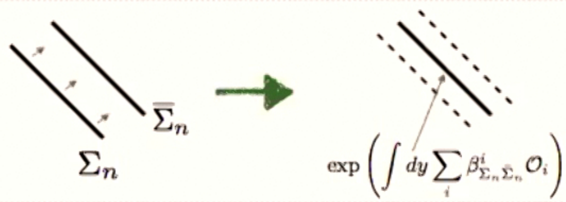
OPE METHODS FOR ENTANGLEMENT



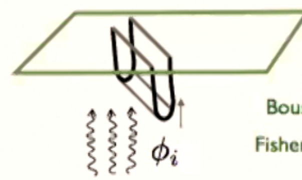
Small `interval' limit of Mutual Information, excited state EE, etc.



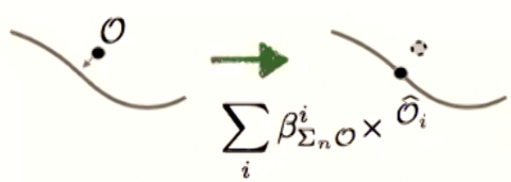
Headrick; Cardy + many more



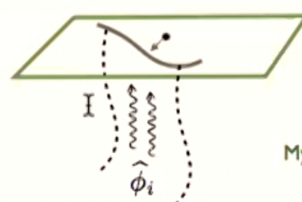
EE on light sheets (Bousso bound), vacuum modular Hamiltonians, etc.



Bousso, Casini, Fisher, Maldacena



Shape deformations of EE and Renyi entropies. Less utilized …



Myers, Smolkin et al.

Recording

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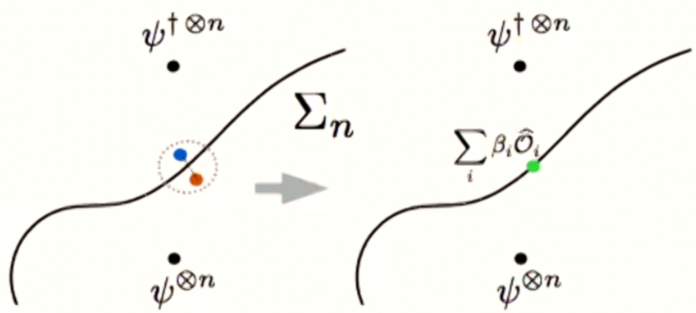
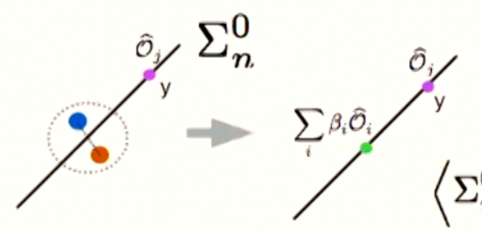
DEFECT OPE



- I. What is the defect spectrum? $\hat{\mathcal{O}}_i$
- II. How to compute β_i ?

II. Computing the dOPE coefficients:



$$\left\langle \Sigma_n^0 \hat{O}_i \hat{O}_j \right\rangle \propto \delta_{ij}$$

Same replacement but in vacuum on flat defect

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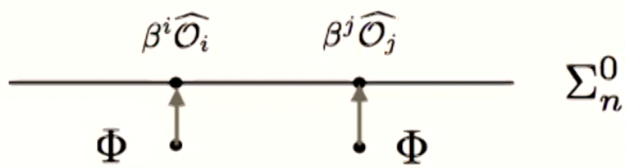
Search

I. DEFECT OPERATOR SPECTRUM

- Consider a two point function in presence of Σ_n^0



$\mathbb{H}_{d-1} \times \mathbb{S}^1_{\beta=2\pi n}$

- Analytically continue $\langle \Sigma_n^0 \Phi\Phi \rangle$ in n (thermal correlator) TF `14
- Extract spectrum by taking limit to twist defect $\widehat{\Delta}(n)$
- Two point correlator fixed in $\lim n \to 1$ by local data of theory

$$n = 1 \quad \langle \Phi\Phi \rangle_{CFT} \qquad \mathcal{O}(n-1) \quad \langle \Phi\Phi T_{\mu\nu} \rangle_{CFT}$$

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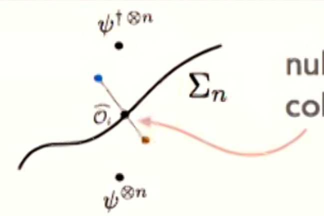
THE SPECTRUM:



null separated and collinear with defect

- Mostly interested in: $\Phi = T_{uu}$ (light-cone limit = lowest twist)
- n=1 then no defect - same spectrum as before (ANEC)

(decomposed using defect symmetries)

Operator	n=1	O(n-1)
$\partial_u^{\ell-2} T_{uu}$	$\hat{\tau} = d-2$ $\ell \geq 2$	$\delta\hat{\tau} =$ $(n-1)\gamma_\ell$
$\mathcal{D}_u$	not seen	$\hat{\tau} = d-2$ $\ell = 1$

A new operator emerges with same twist …. displacement op.

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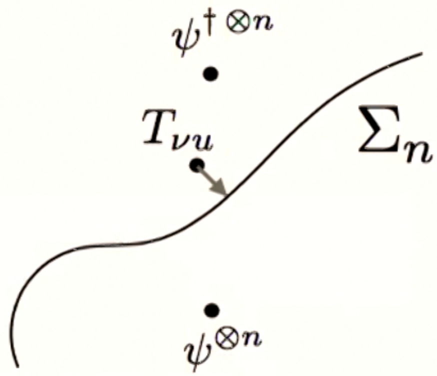
THE DISPLACEMENT OPERATOR



$$\nabla^\nu T_{\nu u}(x)\Sigma_n = \delta_{\Sigma_n}(u,v)\mathcal{D}_u(y)\Sigma_n$$

The displacement operator moves around the defect

$$\lim_{n\to 1}\partial_n \langle \mathcal{D}_u \Sigma_n \rangle = \frac{\delta S_{EE}}{\delta x^-(y)}$$

At this point we have all the ingredients that go into the QNEC. Modular flow is a similar computation (not much more difficult) …

$$f(s) = 1 - e^s u(-uv)^{\frac{d-2}{2}}\mathcal{Q}_u + \dots$$

Recording

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THE DISPLACEMENT OPERATOR

- New operators appear away from n=1 for spinning operators

$$\ell_\Phi \geq 2 \qquad \widehat{\ell} = 1, \ldots, \ell_\Phi - 1$$

- Subject to a higher spin QNEC
- Correspond to fields living on RT surface?
- One point functions of these ops ~ non-linear in the state
- Not really operators ~ limit $n \to 1$ of operators in n-replicated theory

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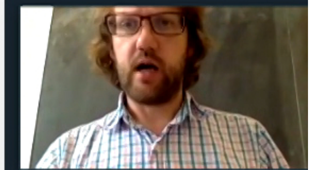
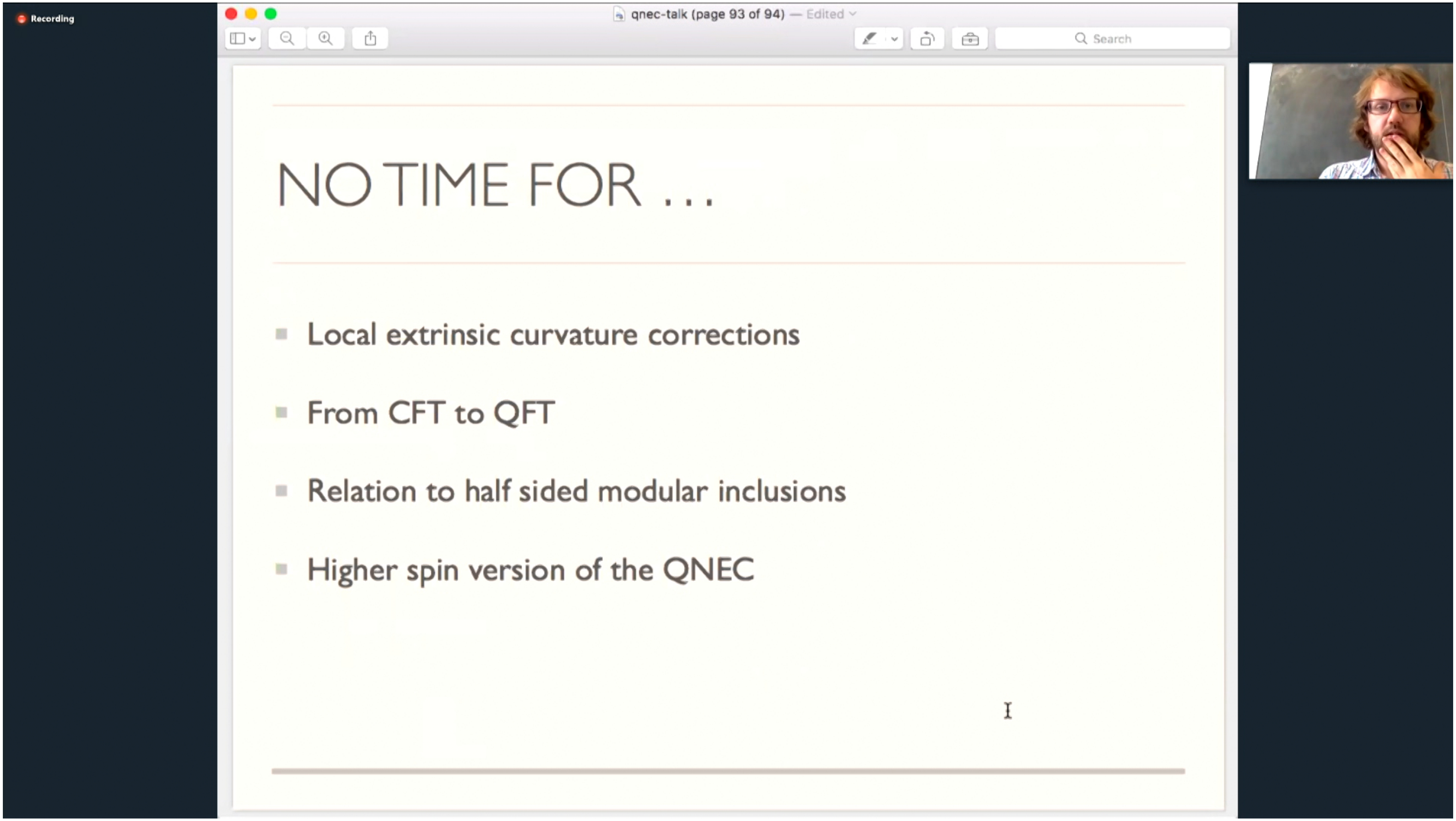


SUMMARY

	ANEC	QNEC
BOUND	$\mathcal{A}_u \geq 0$	$\mathcal{Q}_u \geq 0$
ADS/CFT	Gao-Wald Wall, Kelly `14	Entanglement Wedge Nesting Koeller, Leichenauer, `16
QFT	$\langle\psi\| \mathcal{O}\mathcal{O} \|\psi\rangle$ Hartman et al.'16	$\langle\psi\| \mathcal{O}e^{-isK_B}e^{isK_A}\mathcal{O} \|\psi\rangle$ Balakrishnan et al.'17
BULK?	Regge limit ~ high energy scattering in bulk (stringy) … Camanho et al. ….	???? $s \gg 1$ $v = \text{fixed, small}$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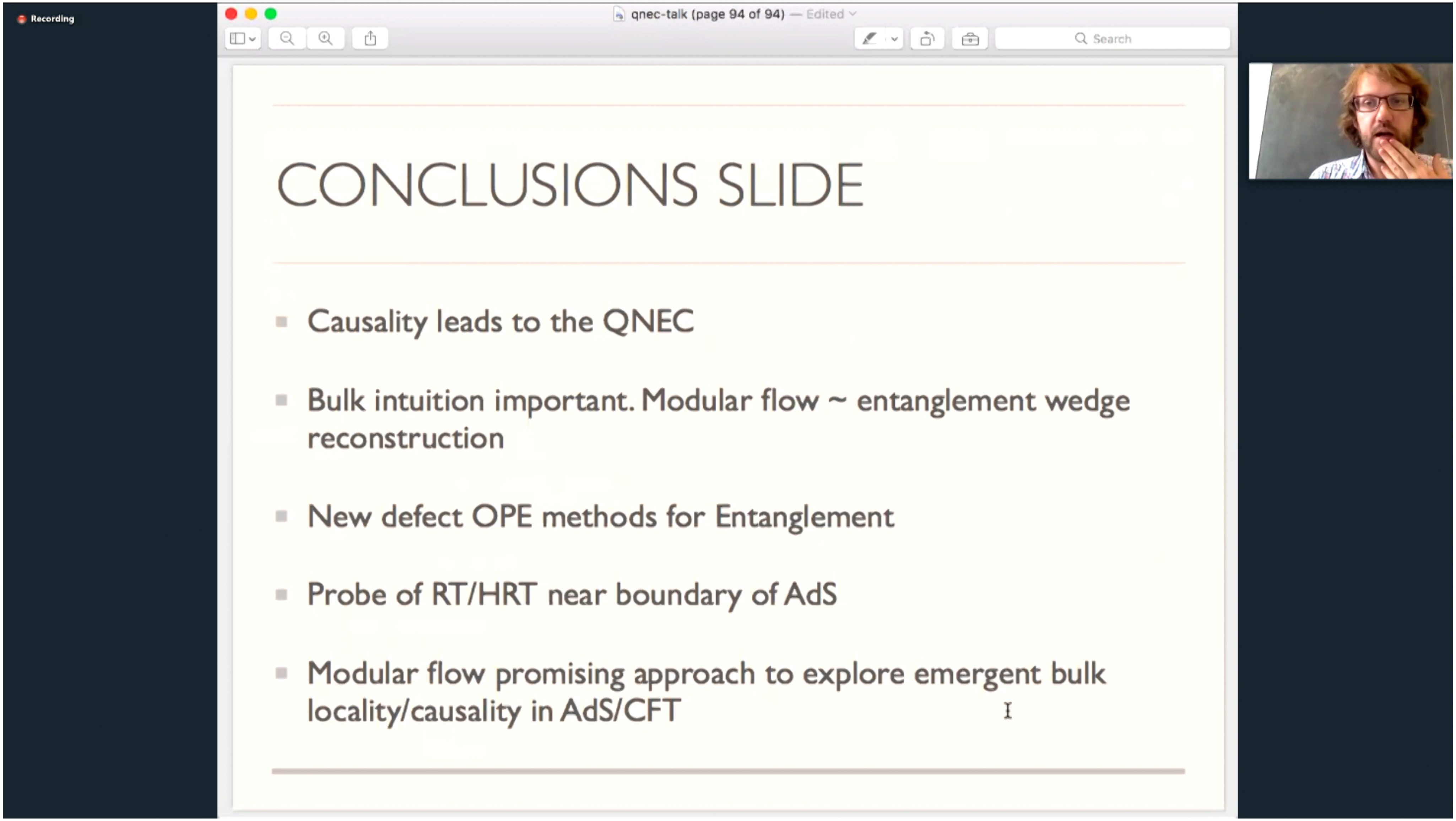
NO TIME FOR …
Local extrinsic curvature corrections
From CFT to QFT
Relation to half sided modular inclusions
Higher spin version of the QNEC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CONCLUSIONS SLIDE
Causality leads to the QNEC
Bulk intuition important. Modular flow ~ entanglement wedge reconstruction
New defect OPE methods for Entanglement
Probe of RT/HRT near boundary of AdS
Modular flow promising approach to explore emergent bulk locality/causality in AdS/CFT