Title: Space time fluctuations in AdS/CFT and Extensions to Minkowski

Speakers: Kathryn Zurek

Series: Cosmology & Gravitation

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Abstract: Zoom Link: https://pitp.zoom.us/j/93581608531?pwd=d3NRQXRGNTNISkhuWmxLYkJMZllTUT09

Based on recent work arXiv:1902.08207 and arXiv:1911.02018 with E. Verlinde.

SPACETIME FLUCTUATIONS IN ADS/ CFT AND EXTENSIONS TO MINKOWSKI

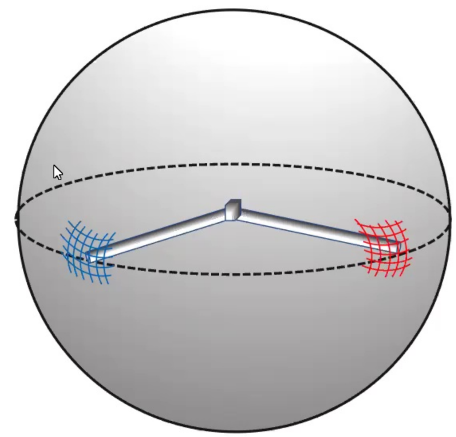
E. Verlinde, KZ 1902.08207
E. Verlinde, KZ 1911.02018

Kathryn M. Zurek

VACUUM FLUCTUATIONS IN SPACETIME AND INFRARED EFFECTS

- The vacuum energy fluctuates

- These vacuum energy fluctuations induce metric fluctuations



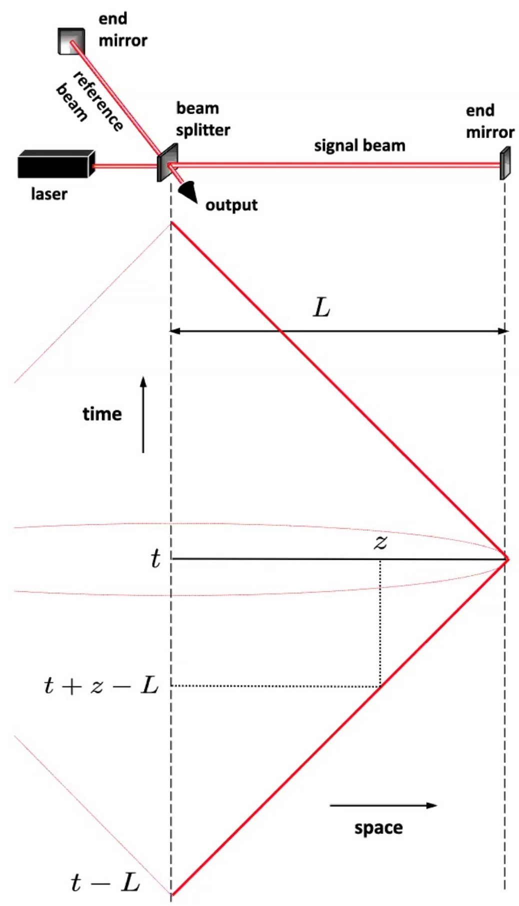
- Metric fluctuations give rise to length fluctuations

- This is an infrared effect. How big is it?

MEASURING LENGTH

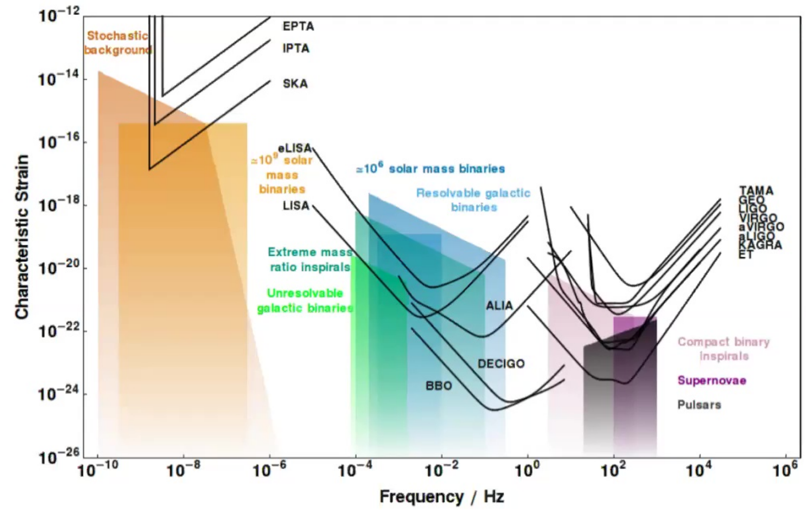
- Draw worldlines of 1 light beam with respect to 2nd reference arm
- An interferometer measures a finite region of space; traces out a causal diamond

$$\delta L(t) = \frac{1}{2}\int_0^L dz\, h(t+z-L)$$



RELEVANT OBSERVABLE — STRAIN OR POWER SPECTRAL DENSITY

- Strain $\sim \dfrac{\delta L}{L} \sim 10^{-20}$



$$\delta L \sim \sqrt{l_p L}$$

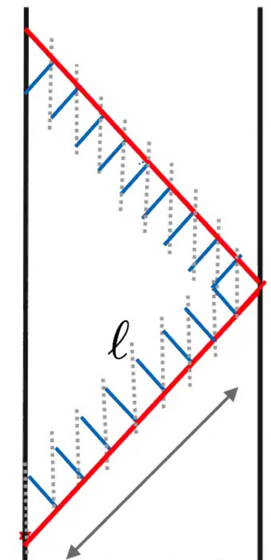
- with peak sensitivity at

$\omega \simeq 1/rL$

Cole, Berry, Moore 1408.0740

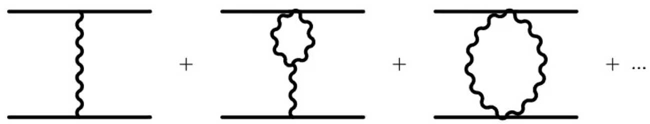
PHYSICAL INTUITION OF SQUARE ROOTS

- Square roots appear in physical contexts where stochastic (thermal) processes are important
- Random walk: $\langle \delta L^2 \rangle = \ell^2 N$ $\qquad N = \dfrac{L}{\ell}$
- ℓ is the diffusion length
- White noise on length scales larger than ℓ



EXPECTATION FOR THE SIZE OF QUANTUM FLUCTUATIONS

- From usual EFT reasoning: $l_p \sim 10^{-35}\ \mathrm{m} \sim 10^{-43}\ \mathrm{s}$



$$V(r) = -\frac{G m_1 m_2}{r}\left(1 + a\frac{G(m_1+m_2)}{rc^2} + b\frac{G\hbar}{r^2c^3}\right)$$

- G_N is the expansion parameter, and quantum effects enter at l_p^2
- Good reason: effects are naturally at Planckian length scales with Planckian frequencies, for which no experiment exists
- However, we know there are cases where large-N effects give rise to enhancements
- And where causal diamonds are involved, there is a natural IR scale: the size of the causal diamond, L

BASIC IDEA — SPECIALIZE TO ADS/CFT FOR COMPUTATION

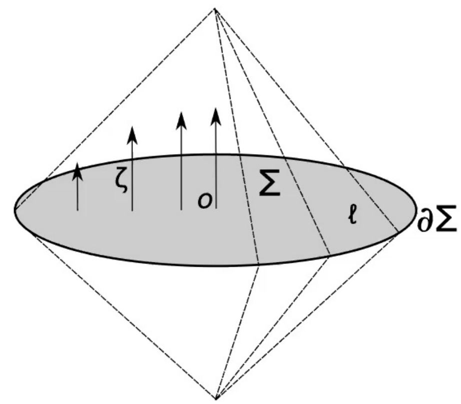
- The vacuum fluctuates
- Energy vanishes integrated over all space in the vacuum

$$H_\xi = \int T_{ab}^{CFT} \xi^a dV^b$$

$$\langle \text{vac} | H_\xi^2 | \text{vac} \rangle = 0$$

- But the stress tensor itself still has a non-trivial two point function

$$\langle \text{vac} | T_{ab}^{CFT}(x) T_{cd}^{CFT}(y) | \text{vac} \rangle \neq 0$$



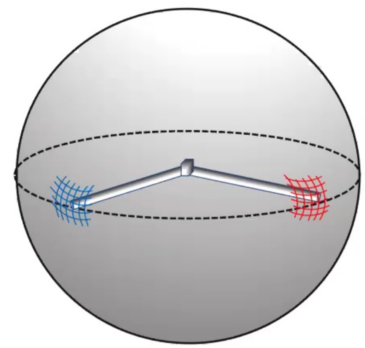
Jacobson 2015

BASIC IDEA — SPECIALIZE TO ADS/CFT FOR COMPUTATION

- The vacuum fluctuates
- Integrated over sub-region, we expect the "modular Hamiltonian" to fluctuate

$$K = \int_B T_{ab}^{CFT} \xi_K^a dB^b$$

$$\langle K^2 \rangle - \langle K \rangle^2 \neq 0$$



- Calculate size of fluctuations and then backreaction of metric on these "energy" fluctuations

OUTLINE

- Review of arguments from 1902.08207
  - Postulate size of energy fluctuations in Minkowski vacuum based on holographic principle
  - Compute resultant length fluctuations
- Go to a theoretically controlled setting: AdS/CFT
  - Make use of extensive results available in literature
  - Few assumptions
  - Calculate same quantities
- Future directions: holography in flat space

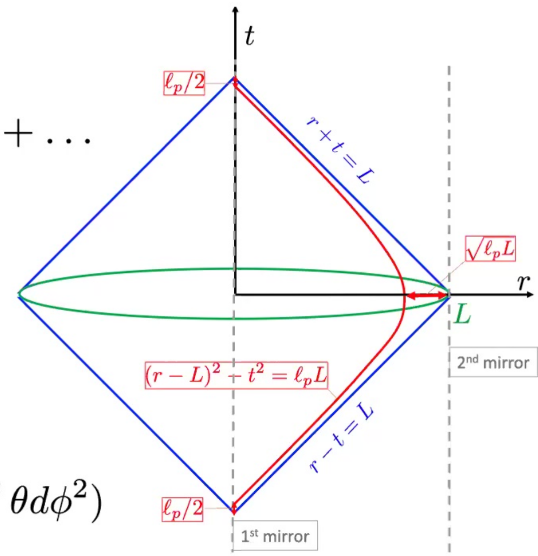
OUR ARGUMENT (3 STEPS)

1. Calculate fluctuations in the energy of the vacuum
   A. In AdS/CFT this can be calculated with no assumptions.
   B. In Minkowski space, assume area law holds.
2. Calculate metric fluctuation from this vacuum energy fluctuation
3. Calculate length fluctuations from metric fluctuations

NEWTONIAN POTENTIAL SOURCES LENGTH FLUCTUATIONS (3)

- Minkowski metric in light cone coordinates

$$ds^2 = dudv + dy^2 + h_{uu}du^2 + h_{vv}dv^2 + \ldots$$



- Bring to form of "topological black hole"

$$ds^2 = -f(R)dT^2 + \frac{dR^2}{f(R)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

- by coordinate transformation

$$(u-L)(v-L) = 4L^2 f(R), \qquad \log\frac{u-L}{v-L} = \frac{T}{L} \qquad f(R) = 1 - \frac{R}{L} + 2\Phi$$

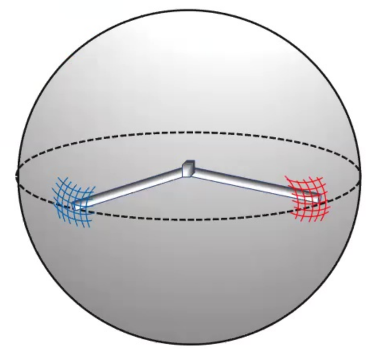
ENERGY FLUCTUATION SOURCES NEWTON POTENTIAL (1+2)

- The vacuum state of any QFT, restricted to the diamond, can be expressed as a thermal density matrix (Casini, Huerta, Myers)

$$\rho = \frac{e^{-\beta E}}{Z} = e^{\beta(F-E)} \qquad F(\beta) = -T_{hor}S_{hor} = -\frac{\beta}{2l_p^2} \qquad \langle \Delta M^2 \rangle = -\frac{\partial^2}{\partial \beta^2}(\beta F) = \frac{1}{l_p^2}$$

"Energy" fluctuations are Planckian

$$\Phi(L) = -\frac{l_p^2 \Delta M}{8\pi L} \quad \Rightarrow \quad \Phi \sim \frac{l_p}{L}$$



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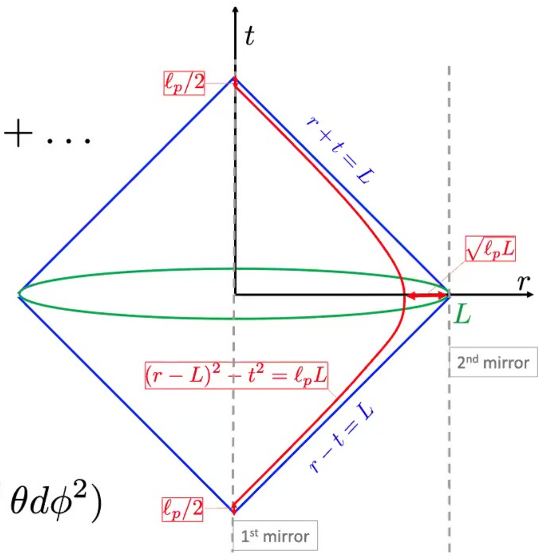

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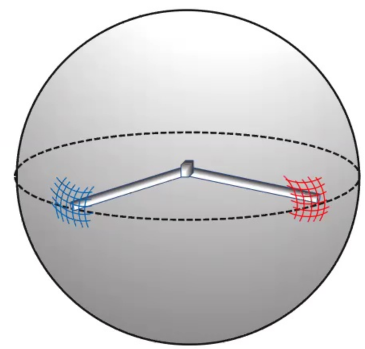


IN MINKOWSKI VACUUM, COMPUTE ENERGY FLUCTUATION (1)

- Postulate size of energy fluctuations based on holographic principle

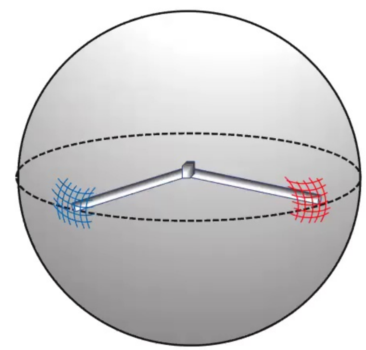
$$S_{hor} = \frac{A}{4G_N} = \frac{8\pi^2 L^2}{l_p^2}$$

- Each d.o.f. has temperature set by size of volume

$$T = \frac{1}{2\pi L}$$

- Statistical argument:

$$\Delta M \sim \sqrt{S}T = \frac{1}{\sqrt{2}l_p}$$



SQUARE ROOTS AND POWER COUNTING

- Note that the field theory calculation of energy fluctuations only involves powers of Newton Constant (Step 1)

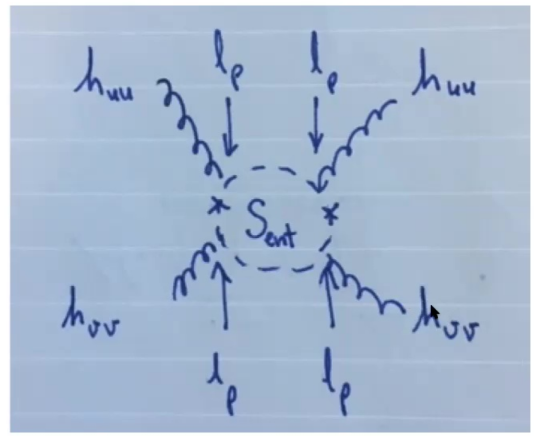
$$\langle \Delta M^2 \rangle = -\frac{\partial^2}{\partial \beta^2}(\beta F) = \frac{1}{l_p^2}$$

- No square roots!
- Square root enters in the transformation from Rindler coordinates to flat space observable (Step 3)

$$\Phi \sim h_{uu} h_{vv} \sim \frac{\delta L^2}{L^2}$$

SQUARE ROOTS AND POWER COUNTING

$$\delta L^4 \sim G^2 \frac{A}{4G}$$



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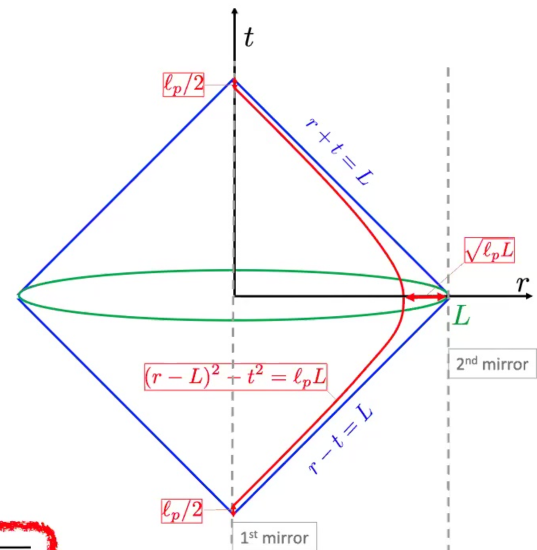
$$\Phi \sim h_{uu}h_{vv} \sim \frac{\delta L^2}{L^2}$$

$$\Phi \sim \frac{l_p}{L} \quad \Rightarrow \quad \boxed{\delta L \sim \sqrt{l_p L}}$$



“

AdS/CFT $\langle K^2 \rangle - \langle K \rangle^2 \neq 0$

Where microscopics are under control

SET-UP

- d+1 dimensional AdS

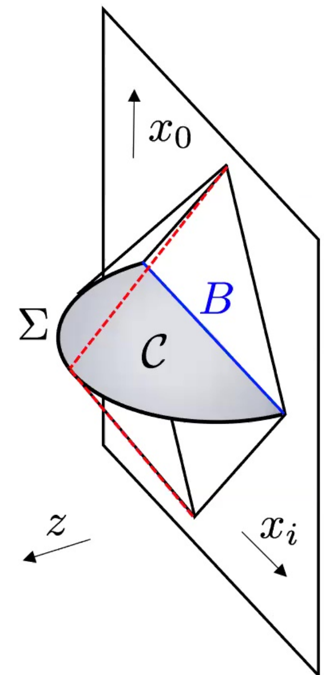
$$ds^2 = L^2 \frac{dz^2 + dx_i^2 - dx_0^2}{z^2}$$

- Finite spherical region on boundary B

$$R^2 - z^2 - x_i^2 + x_0^2 \geq 2R|x_0|$$

- Corresponds to causal diamond in bulk anchored to B

$$K = \int_B T_{ab}^{CFT} \xi_K^a dB^b$$

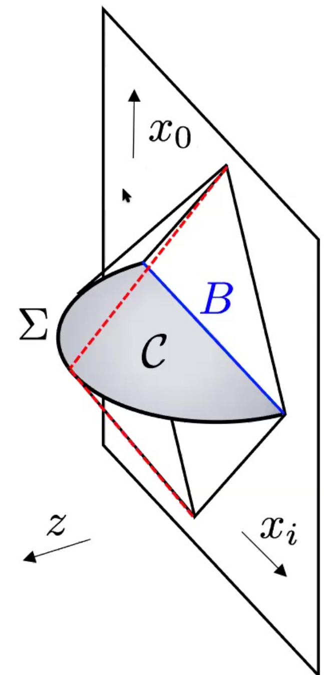


BOUNDARY THEORY RESTRICTED TO CAUSAL DIAMOND

- The vacuum state of any QFT, restricted to the diamond, can be expressed as a thermal density matrix

$$\sigma = \mathrm{tr}_{\mathcal{H}_{\overline{B}}}\left(|vac\rangle \langle vac| \right)$$

$$\sigma = \frac{e^{-K}}{Z} \qquad \text{with} \qquad Z = \mathrm{tr}(e^{-K})$$



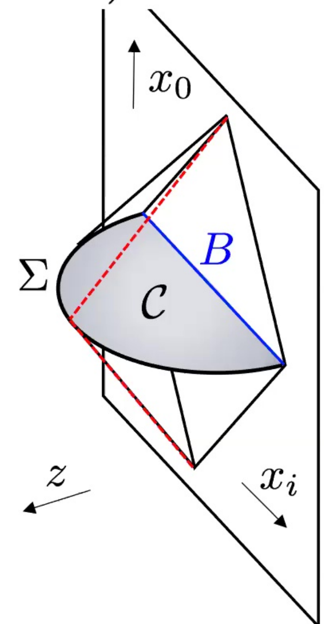
BULK THEORY RESTRICTED TO CAUSAL DIAMOND

- Describable by "topological black hole"

$$\frac{R^2 - z^2 - x_i^2 + x_0^2}{2Rz} = \left(\frac{r^2}{L^2} - 1\right)^{\frac{1}{2}} \cosh\frac{t}{L}, \qquad \frac{x_0}{z} = \left(\frac{r^2}{L^2} - 1\right)^{\frac{1}{2}} \sinh\frac{t}{L}$$

$$ds^2 = -\left(\frac{r^2}{L^2} - 1\right) dt^2 + \left(\frac{r^2}{L^2} - 1\right)^{-1} dr^2 + r^2 d\Sigma_{d-1}^2$$

- By AdS/CFT correspondence, thermal bath of CFT is related to the appropriate black hole in the bulk



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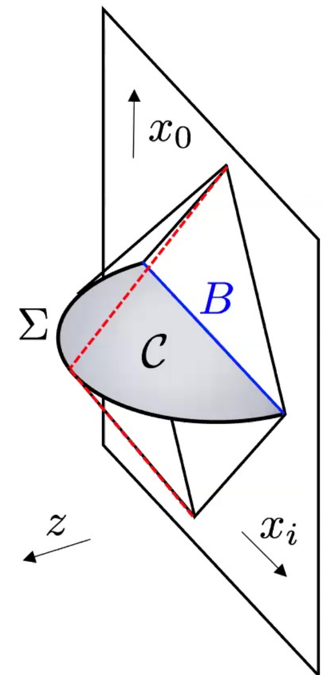

FLUCTUATIONS IN "MODULAR ENERGY" OF CFT (1)

- Thermal density matrix of CFT —> Free Energy

$$F_\beta = -\frac{1}{\beta}\log \mathrm{tr}\left(e^{-\beta K}\right)$$

- In principle, allows to calculate expectation values

$$\langle K^2 \rangle - \langle K \rangle^2 = -\frac{\partial^2}{\partial \beta^2}\left(\beta F_\beta\right)$$

- In CFT, done by E. Perlmutter
- We used holographic entropy to calculate this quantity

CALCULATING THE BULK MODULAR HAMILTONIAN (1)

- According to AdS/CFT dictionary, entanglement entropy of boundary is dual to horizon entropy of topological black hole in the bulk
- Use "replica trick" — replace density matrix with n copies

$$\rho_n = \frac{\sigma^n}{\mathrm{tr}\left(\sigma^n\right)} = \frac{e^{-nK}}{Z_n} \qquad T_n = \frac{1}{2\pi L n}$$

$$F_n = -\frac{1}{n}\log\left(\mathrm{tr}\left(\sigma^n\right)\right)$$

$$\langle K \rangle = \frac{d}{dn}\left(nF_n\right)\Big|_{n=1}$$

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- Evaluate free energies holographically

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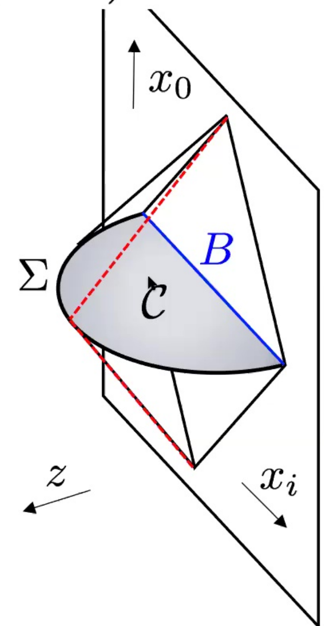

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- Evaluate free energies holographically

CALCULATING THE BULK MODULAR HAMILTONIAN (1)

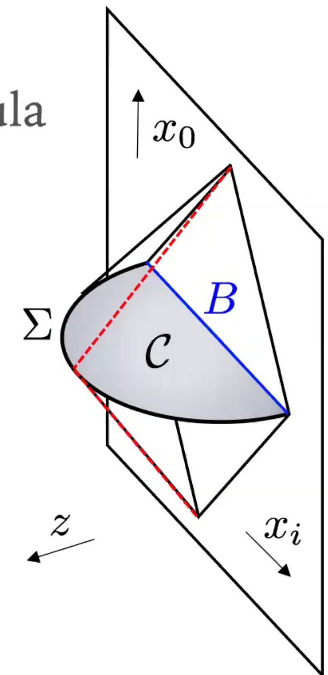
- According to AdS/CFT dictionary, entanglement entropy of boundary is dual to horizon entropy of topological black hole in the bulk
- Evaluate holographically utilizing RT formula

Hung, Myers, Smolkin, Yale *Xi Dong*

$$F(T) = E - TS$$

$$nF_n = \frac{1}{T(x_n)}\left[-T(x)S(x)\Big|_1^{x_n} + \int_1^{x_n} T(x)dS(x)\right]$$

$$S(x) = \frac{A(\Sigma)}{4G}x^{d-1}$$



BULK MODULAR HAMILTONIAN (1)

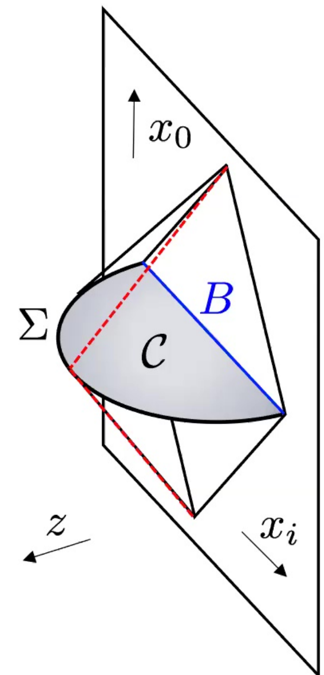
- Main result:

$$\langle \Delta K^2 \rangle = \frac{A(\Sigma)}{4G}$$

- How does the bulk metric react?

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Sigma_{d-1}^2$$

$$f(r) = \frac{r^2}{L^2} - 1 - 2\Phi \frac{L^{d-2}}{r^{d-2}}$$



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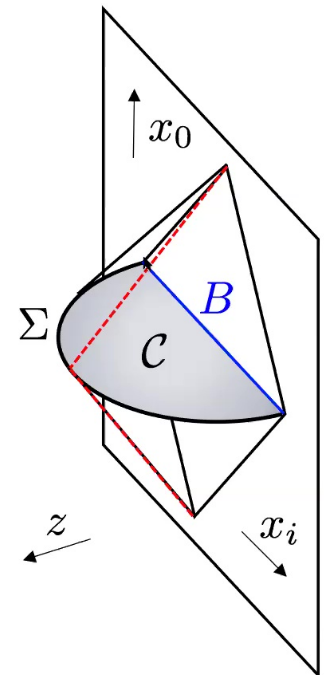


BULK MODULAR HAMILTONIAN — DOES IT GRAVITATE?

- Modular energy of boundary CFT restricted to diamond is related to a minimal surface in bulk — Ryu-Takayanagi:

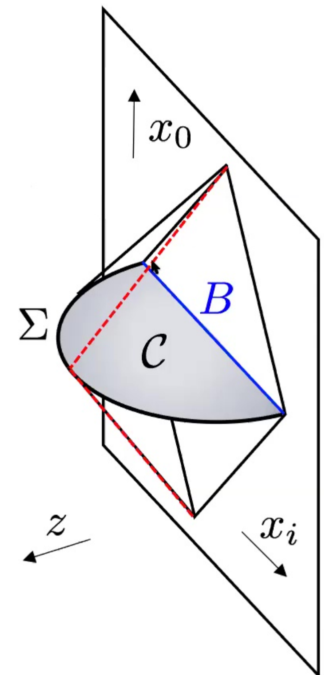
$$\langle K \rangle = S_{\rm ent} = \frac{A(\Sigma)}{4G}$$

- Trivially implies

$$K = \frac{A(\Sigma)}{4G} \cdot \mathbf{1} + \Delta K$$

- According to JLMS, ΔK is the *bulk* modular Hamiltonian — it gravitates!

$$\Delta K = \int_{\mathcal{C}} \xi_K^{\mu} T_{\mu\nu}^{bulk} d\mathcal{C}^{\nu}$$



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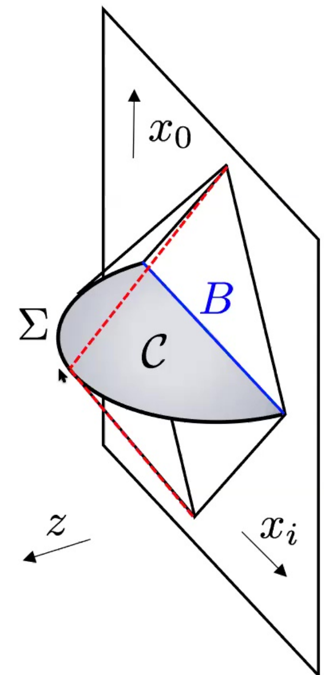


GRAVITATIONAL POTENTIAL AND MASS (2)

- Fluctuations in the modular Hamiltonian behave like a mass — they gravitate!

$$M = \frac{1}{2\pi L}\Big(K - \langle K \rangle\Big)$$

- Show utilizing first law of black hole thermodynamics

$$dM = TdS$$

- The vacuum fluctuation induces a non-zero gravitational potential

$$\Phi = \frac{8\pi GM}{(d-1)V_{d-1}L^{d-2}}$$

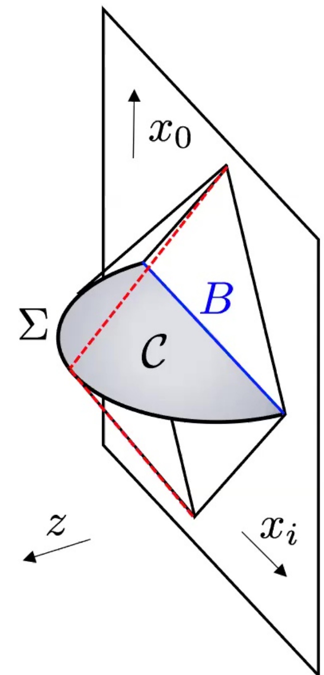
COMMENTS ON REGULARIZATION

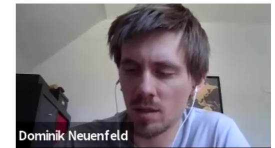
- RT surface is formally infinite and must be regularized

$$\Phi = \frac{8\pi G M}{(d-1)V_{d-1}L^{d-2}}$$

$$A(\Sigma) = L^{d-1}V_{d-1}$$

$$V_{d-1} = \Omega_{d-2}\int_0^{\chi_a} d\chi \, \sinh^{d-2}\chi$$





FINAL RESULT FOR METRIC FLUCTUATION AND MODULAR HAMILTONIAN (2)

$$\Phi = \frac{\Delta K}{(d-1)} \frac{4G}{A(\Sigma)}$$

- It says that the modular Hamiltonian in the bulk sources metric fluctuations

$$\langle \Phi^2 \rangle = \frac{\langle \Delta K^2 \rangle}{(d-1)^2} \left(\frac{4G}{A(\Sigma)} \right)^2 = \frac{1}{(d-1)^2} \frac{4G}{A(\Sigma)}$$

COMMENTS ON REGULARIZATION

➤ RT surface is formally infinite and must be regularized

$$\Phi = \frac{8\pi G M}{(d-1)V_{d-1}L^{d-2}}$$

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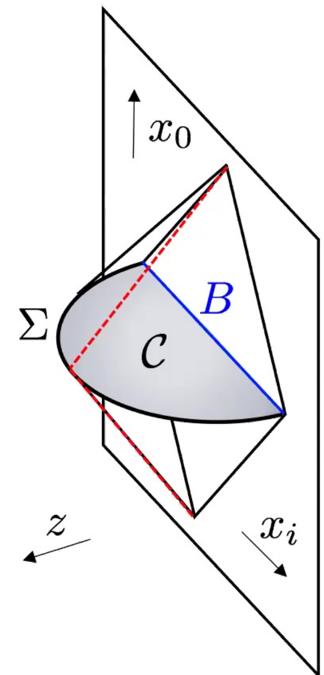
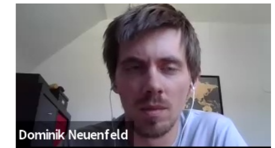
$$V_{d-1} = \Omega_{d-2}\int_0^{\chi_c} d\chi \, \sinh^{d-2}\chi$$





FLUCTUATIONS IN LIGHT ARRIVAL TIME (3)

- In unperturbed metric, light trajectory at:

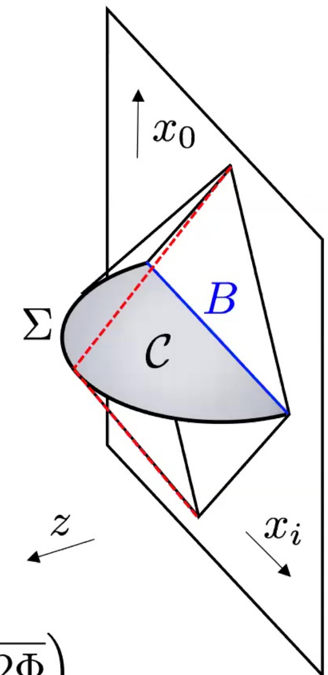
$$x_i = 0 \qquad x_0^e = -R + z_c \qquad x_0^r = R - z_c$$

- Turn on gravitational potential in the bulk and compute change in size of causal diamond

$$\left(\frac{(R-x_0)^2 - z^2 - x_i^2}{2Rz}\right)\left(\frac{(R+x_0)^2 - z^2 - x_i^2}{2Rz}\right) = 2\Phi$$

$$\frac{R^2 - z^2}{2Rz} = \pm\sqrt{2\Phi}$$

$$\Rightarrow \quad z^{reflection} = R\left(\sqrt{1+2\Phi} \pm \sqrt{2\Phi}\right)$$



FINAL RESULT FOR METRIC FLUCTUATION AND MODULAR HAMILTONIAN (2)

$$\Phi = \frac{\Delta K}{(d-1)} \frac{4G}{A(\Sigma)}$$

- It says that the modular Hamiltonian in the bulk sources metric fluctuations

$$\langle \Phi^2 \rangle = \frac{\langle \Delta K^2 \rangle}{(d-1)^2} \left(\frac{4G}{A(\Sigma)} \right)^2 = \frac{1}{(d-1)^2} \frac{4G}{A(\Sigma)}$$

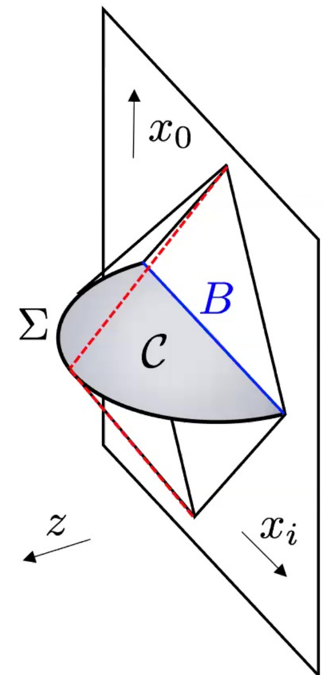
RANDALL-SUNDRUM II SET-UP

- Boundary pulled into bulk, inducing gravity on the brane

$$\frac{\Delta T^2_{r.t.}}{T^2_{r.t.}} = \frac{2}{d-1}\sqrt{\frac{4G}{A(\Sigma)}}$$

$$\frac{\Delta T^2_{r.t.}}{T^2_{r.t.}} \sim \sqrt{\frac{G_{bulk}}{L^{d-1}e^{(d-2)\chi_c}}} \overset{d=4}{\sim} \sqrt{\frac{G_{bdy}}{T^2_{r.t.}}}$$

Agrees with Minkowski result!



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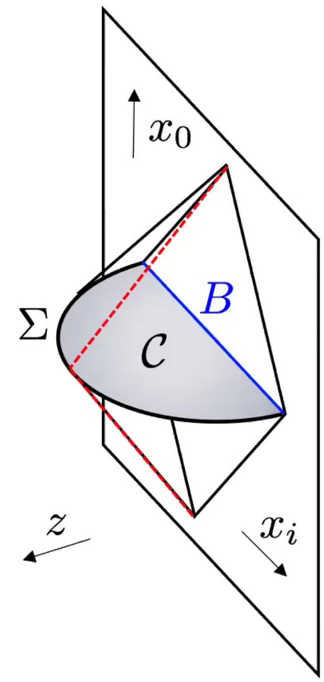

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RECALL OUTLINE OF ARGUMENT

1. Calculate fluctuations in the energy of the vacuum
   A. In AdS/CFT this can be calculated with no assumptions.
   B. In Minkowski space, one assumption must be made.
2. Calculate metric response to this vacuum energy fluctuation
3. Calculate length fluctuations from metric fluctuations and turn into observable

$$S = \frac{A}{4G_N}$$

$$\langle K^2 \rangle - \langle K \rangle^2 = \frac{A(\Sigma)}{4G}$$

Can this result be derived in EFT?

Yes. Well-known that entanglement entropy in field theories scales with area

Area and Entropy, Srednicki '93

Callan and Wilczek '94

Cooperman and Luty '14

Gravitons, Benedetti, Casini '19

kzurek@caltech.edu

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Flat Space

$$\frac{\delta L^2}{L^2} = \frac{\delta v(L)\delta u(L)}{L^2} = 2\Phi$$

AdS case

$$\left(\frac{(R-x_0)^2 - z^2 - x_i^2}{2Rz}\right)\left(\frac{(R+x_0)^2 - z^2 - x_i^2}{2Rz}\right) = 2\Phi$$

We would like to have an independent formulation

SUMMARY

- Thinking about *observational consequences* of quantum gravity
- Led to asking new questions about well-studied system in AdS/CFT
- Still open questions to address — RS braneworld, EFT formulation, OTOCs
- This is fundamentally about the nature of the vacuum in a quantum theory of gravity
- Implications for cosmology and astrophysics
- *I think this deserves attention*

FLUCTUATIONS IN "MODULAR ENERGY" OF CFT (1)

- Thermal density matrix of CFT —> Free Energy

$$F_\beta = -\frac{1}{\beta} \log \mathrm{tr}\left(e^{-\beta K}\right)$$

- In principle, allows to calculate expectation values

$$\langle K^2 \rangle - \langle K \rangle^2 = -\frac{\partial^2}{\partial \beta^2}\left(\beta F_\beta\right)$$

- In CFT, done by E. Perlmutter
- We used holographic entropy to calculate this quantity