Title: From Shockwaves to Gravitational Memory and Fluids: Finding Connections through Observational Signatures

Speakers: Kathryn Zurek

Series: Colloquium

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Abstract: Abstract TBA

Zoom link

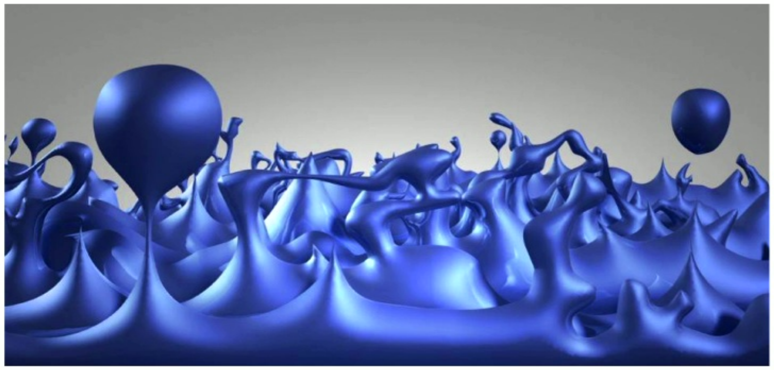
From Shockwaves to Gravitational Memory and Fluids: Finding Connections through Observational Signatures

Kathryn Zurek

Motivation: Understanding Spacetime Fluctuations

And Possible Observational Signatures

- Traditional view: quantum gravity effects visible only at ultrashort distances



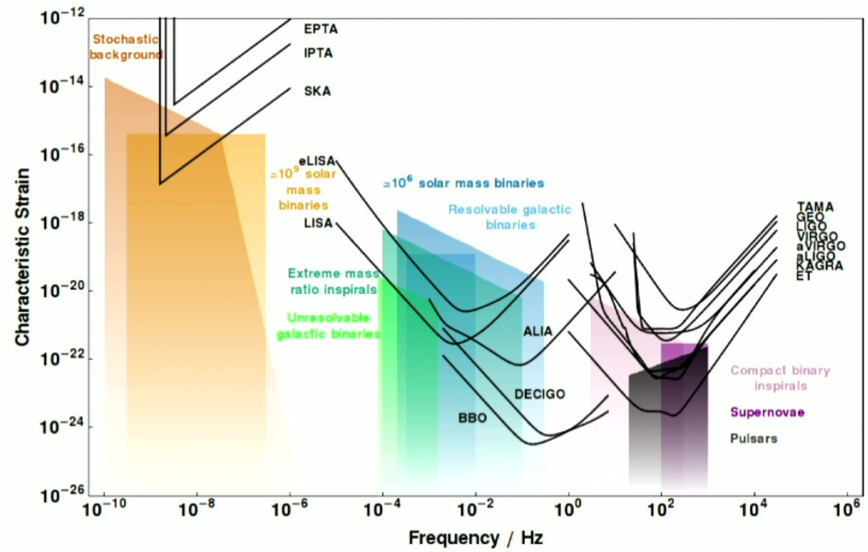
$$l_p \sim 10^{-35}\ \mathrm{m} \sim 10^{-43}\ \mathrm{s}$$

What Length Fluctuations Can be Measured?

in a laboratory setting, e.g. in LIGO

$$\frac{\delta L}{L} \sim 10^{-20}$$

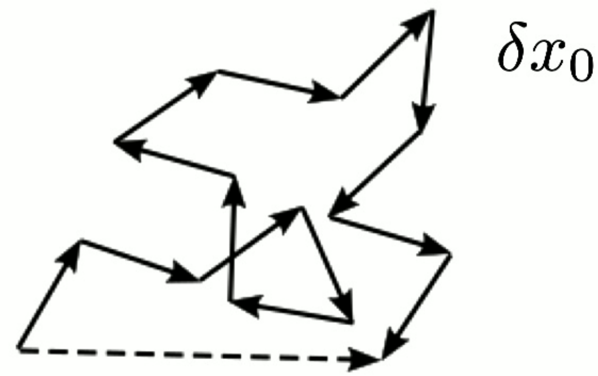
$$\delta L \sim \sqrt{l_p L}$$



Very small, but much larger than Planckian fluctuations

Brownian Noise

UV effects can be transmuted in infrared



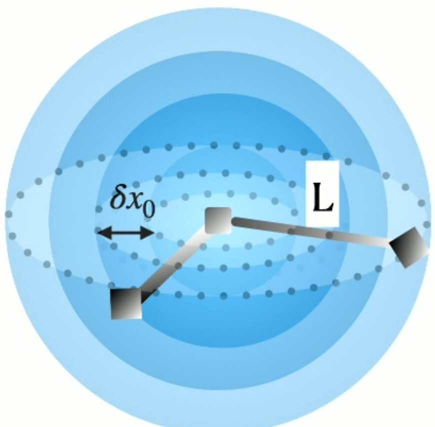
$$\langle x^2 \rangle = 2DT$$

$D \sim \delta x_0$ — UV Scale

Observing Time — IR Scale

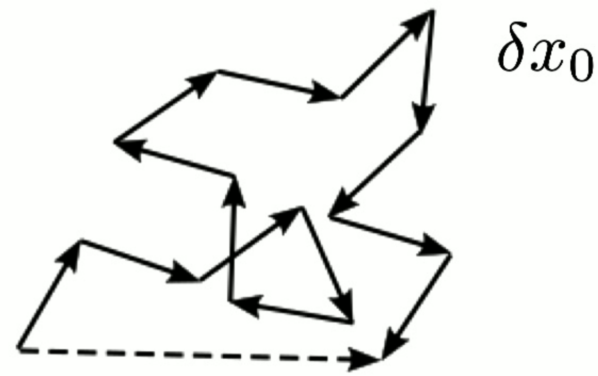
Brownian Noise

In the Causal Development of a Region of Spacetime



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

UV Scale IR Scale



$$\langle x^2 \rangle = 2DT \sim N\delta x_0^2$$

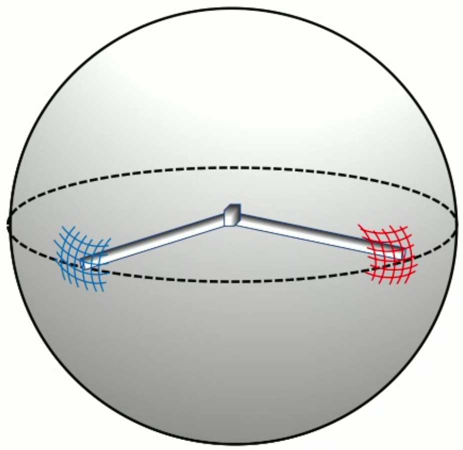
$$D \sim \delta x_0 \qquad N = \frac{T}{\delta x_0}$$

UV Scale IR Scale

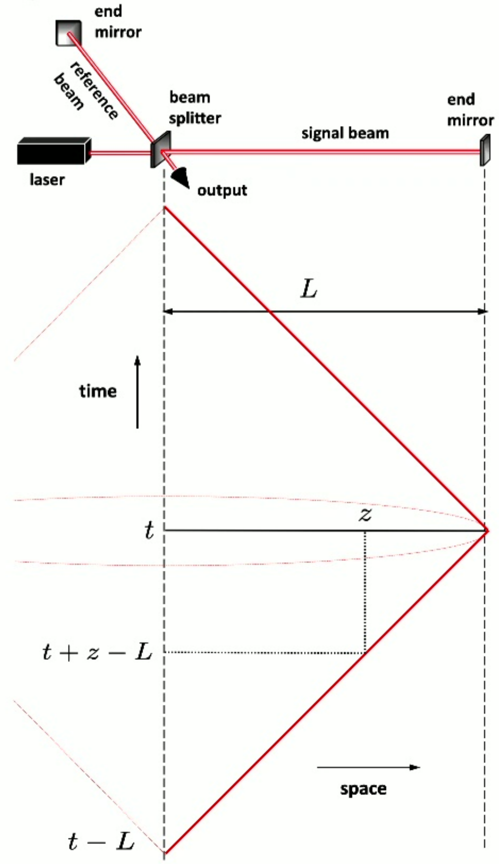
Quantum Uncertainty at Horizons

An Experimental Measurement Defines a Horizon

- Part of the spacetime is observed, and part is outside of the light sheet



- Gravitational Wave Interferometers Trace a Causal Diamond



Black Holes Vs. Flat Empty Space

The Topological Black Hole

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

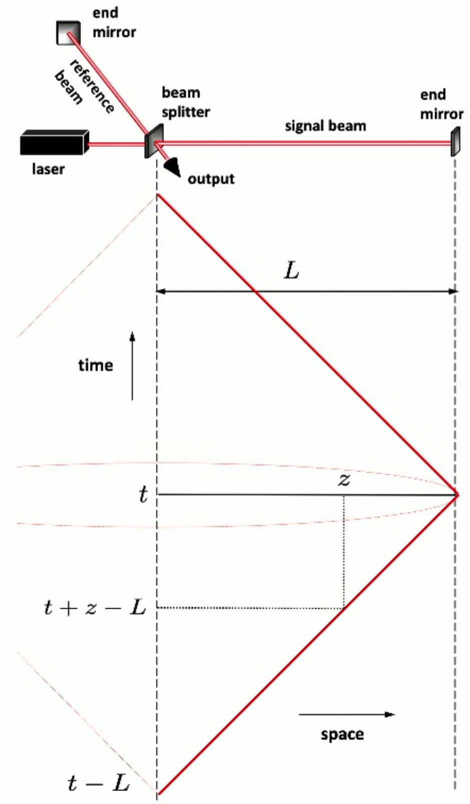
- As long as we are interested in only the part of spacetime inside the causal diamond, the metric in some common spacetimes can be mapped to "topological black hole"

$$ds^2 = dudv + dy^2$$

$$\Downarrow$$

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

$$f(R) = 1 - \frac{R}{L} + 2\Phi$$



Our Argument: Calculate Vacuum Fluctuation

Step 1

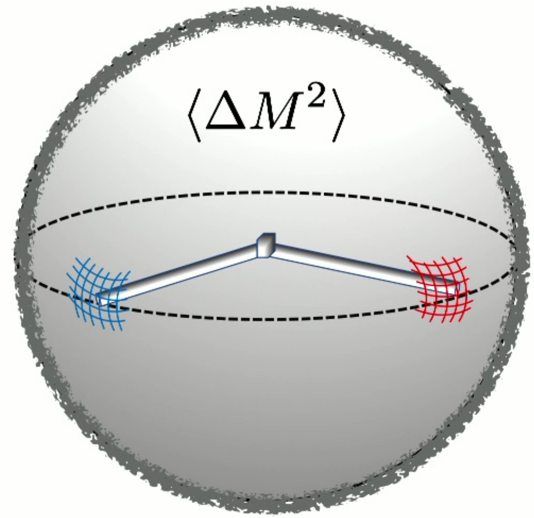
- Number of holographic degrees of freedom is the entropy

$$S = \frac{A}{4G_N} = \frac{8\pi^2 R^2}{l_p^2}$$

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

$$T = \frac{1}{4\pi R}$$

- Statistical argument: $\Delta M \sim \sqrt{S}T = \frac{1}{\sqrt{2}l_p}$



Our Argument: Vacuum Fluctuation Sources Metric Fluctuation

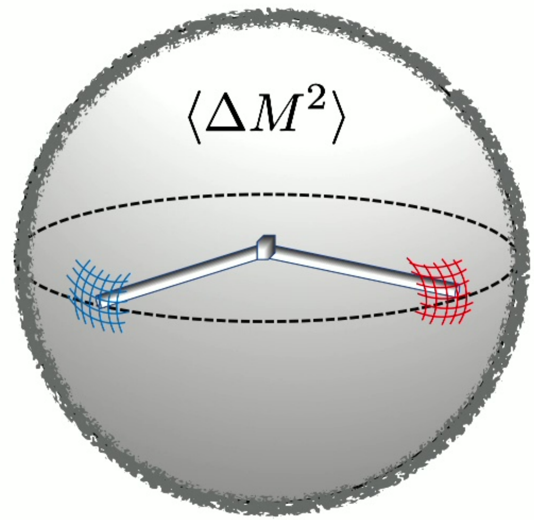
Step 2

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

$$\Rightarrow \quad \Phi \sim \frac{l_p}{L}$$

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

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



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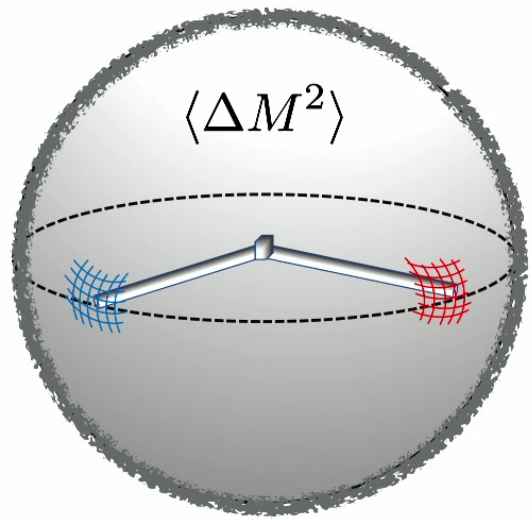

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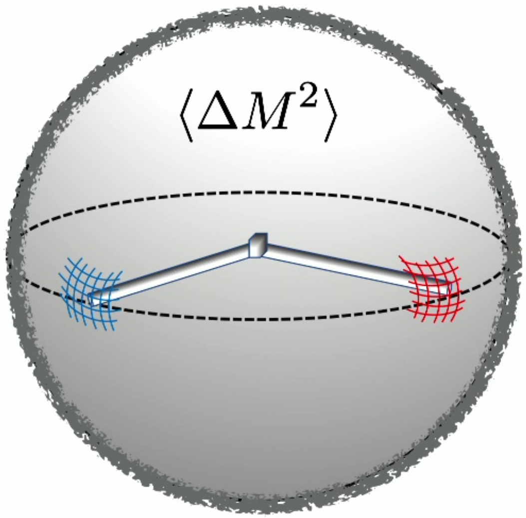

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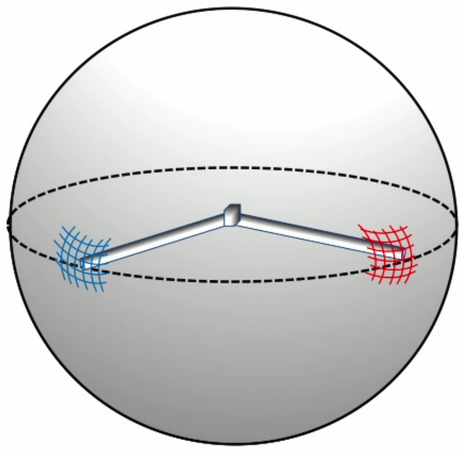

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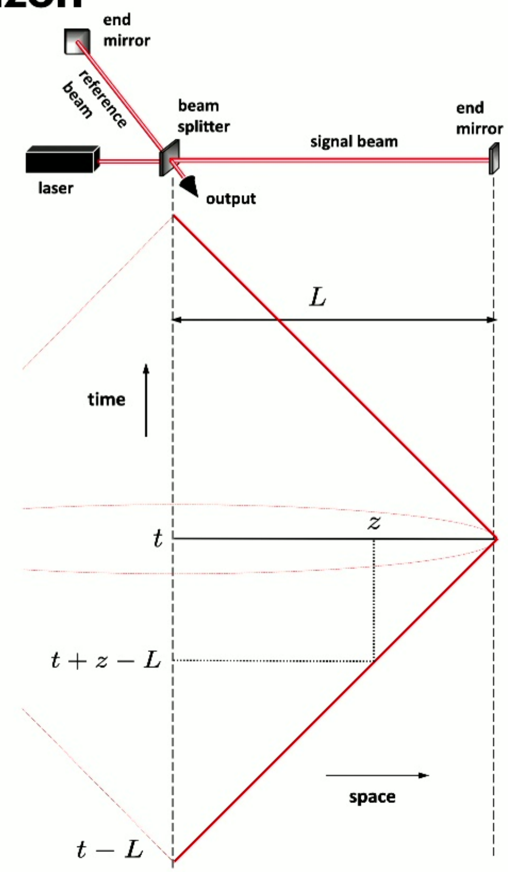

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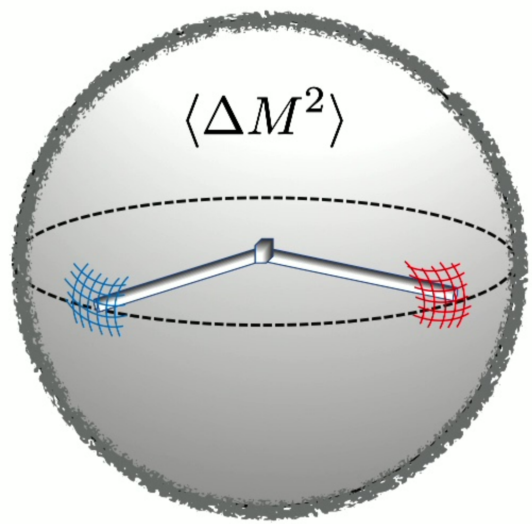


Are these 2 steps justified?

(The effect is large)

- Do horizons in flat empty space have an entropy associated with them, and do these degrees of freedom have QM “Mass” fluctuations?

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

- Does spacetime respond to these fluctuations (in a particular way)?

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

A Web of Soft Equivalences

Gravity in the Soft Limit

Observable?
TBH Mass Fluctuations

S_{ent}

$\langle \Delta K^2 \rangle$

Modular Ham K

⟺

Shockwave

Momenta P

Light Ray Shifts X

Shockwave on-shell action = Bdry action in soft-limit

⟺

Memory

News N

Shear C

Soft Effective Action = Soft Charge

$$K \equiv \int d^2z \gamma_{z\bar{z}} \int_0^\infty dx^- X^- T_{--}$$

$$\langle \Delta K^2 \rangle = \langle K \rangle \propto A(\Sigma)$$

$$S_{\text{VZ}} = \int d^2z \gamma_{z\bar{z}} X^- P_-$$

$$[X^+(z,\bar{z}), X^-(z',\bar{z}')] = 8\pi i G_N G(z-z')$$

$$[P_-(z,\bar{z}), X^-(z',\bar{z}')] = -i\gamma^{z\bar{z}}\delta^{(2)}(z-z')$$

$$S_{\text{soft}} = -\frac{i}{c_{1,1}} \int d^2z \gamma_{z\bar{z}} \tilde{C}^a(z) N_a(z)$$

$$[N(z,\bar{z}), C(z',\bar{z}')] = 8\pi i G_N S \log|z-z'|^2$$

Outline

Connections between "mass" fluctuations, shockwave geometries, gravitational memory and Rindler Fluids

- To examine these postulates we will make new connections between old ideas

1. "Mass" fluctuations = modular fluctuations = quantum fluctuations in shockwave geometries   Verlinde, KZ 2208.01059

2. Shockwave geometries are diffeomorphic to memory geometries

   ➡ 't Hooft commutators = soft commutators

   He, Raclariu, KZ 2305.14411, WIP   He, Mitra, Sivaramakrishnan, KZ 2403.14502, He, Mitra, KZ WIP

3. Shockwave geometries also have a description as a Rindler fluid

   Fluctuations accumulate

   Bak, Keeler, Zhang, KZ 2403.18013   Zhang, KZ 2304.12349

Black Hole - (Empty!) Causal Diamond Dictionary

Mathematical equivalence between two very different physical systems

Black Hole	Causal Diamond
Horizon	Horizon defined by null rays
Black Hole Temperature	Size of Causal Diamond $T \sim 1/L$
Black Hole Mass	Modular Fluctuation $M = \frac{1}{2\pi L}\Big(K - \langle K\rangle\Big)$
Thermodynamic Free Energy	Partition Function $F = -\frac{1}{\beta}\log\,\mathrm{tr}\left(e^{-\beta K}\right)$
Thermodynamic Entropy	Entanglement Entropy $S = \langle K\rangle = \frac{A}{4G}$

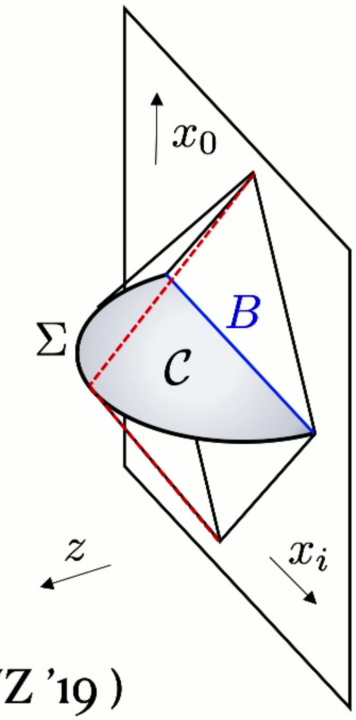
Dictionary can be shown in AdS/CFT

Precisely.

- The Modular Fluctuations Were Known in AdS/CFT

$$K = \int_B T_{ab}^{CFT} \xi_K^a dB^b \qquad F_\beta = -\frac{1}{\beta} \log \mathrm{tr}\left(e^{-\beta K}\right)$$

$$\langle K \rangle = S_{\mathrm{ent}} = \langle \Delta K^2 \rangle = \frac{A(\Sigma)}{4G_N}$$



- Can either calculate on the CFT side (Perlmutter '13)
- Or on the gravity side (Nakaguchi, Nishioka '16, de Boer et al '18, VZ '19)

What is the physical basis for modular fluctuations?

Understanding the possible application to flat space

- There is evidence for an analogue of the modular Hamiltonian for flat space (Banks, KZ 2108.04806)
- K defines partition function, and for any QFT restricted to diamond

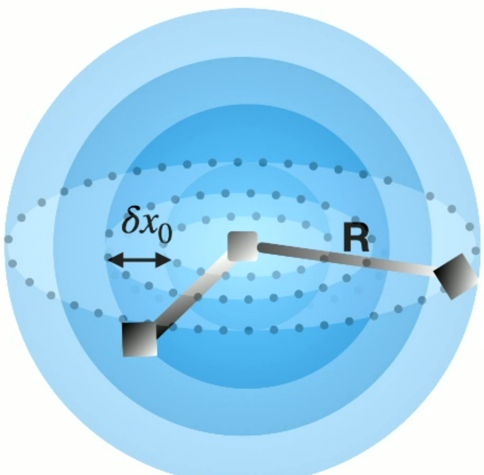
$$\rho = \frac{e^{-K}}{\mathrm{Tr}(e^{-K})} \qquad\qquad K = \int_B T_{ab}^{CFT}\,\xi_K^a\,dB^b$$

- Intuition: in the IR, gravity has conformal behavior. T is the stress tensor of all effectively massless d.o.f.
- There is a universal relation between K and its fluctuations $\langle \Delta K^2 \rangle = \langle K \rangle = \frac{A(\Sigma_{d-2})}{4G_d}$

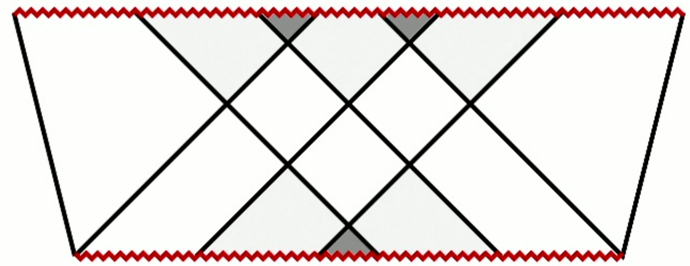
What is the physical basis for modular fluctuations?

Shockwaves.

- Hypothesis: shockwaves from *vacuum fluctuations* generate modular fluctuations
- Modular fluctuations source spacetime fluctuations



$$h_{\pm\pm} = \ell_p^2 \int d^2 z \gamma_{z\bar{z}} G(z - z') T_{\pm\pm}(z)$$



Multiple shocks

$$X^{\pm} = \int dx^{\mp} h_{\mp\mp}$$

Laboratory for Quantum Fluctuations in Spacetime

Shockwaves and the 't Hooft Commutation Relations

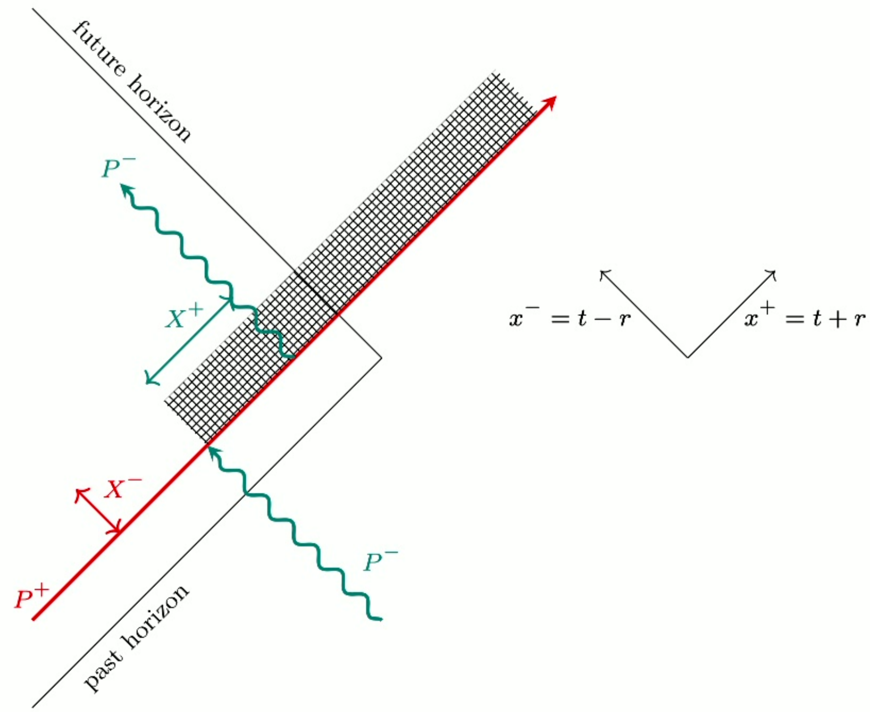
- Shockwave spacetime in 4-d, originally studied in a black hole background
- Einstein's equations in flat space:

$$\delta x^-(z) = 4\pi G_N \int d^2z'\,\gamma_{z'\bar{z}'}\,G(z-z')p^-(z')$$

$$\Box G(z-z') = 2\gamma^{z\bar{z}}\delta^{(2)}(z-z')$$

- in 4-d:

$$G(z-z') = \frac{1}{2\pi}\log|z-z'|^2$$

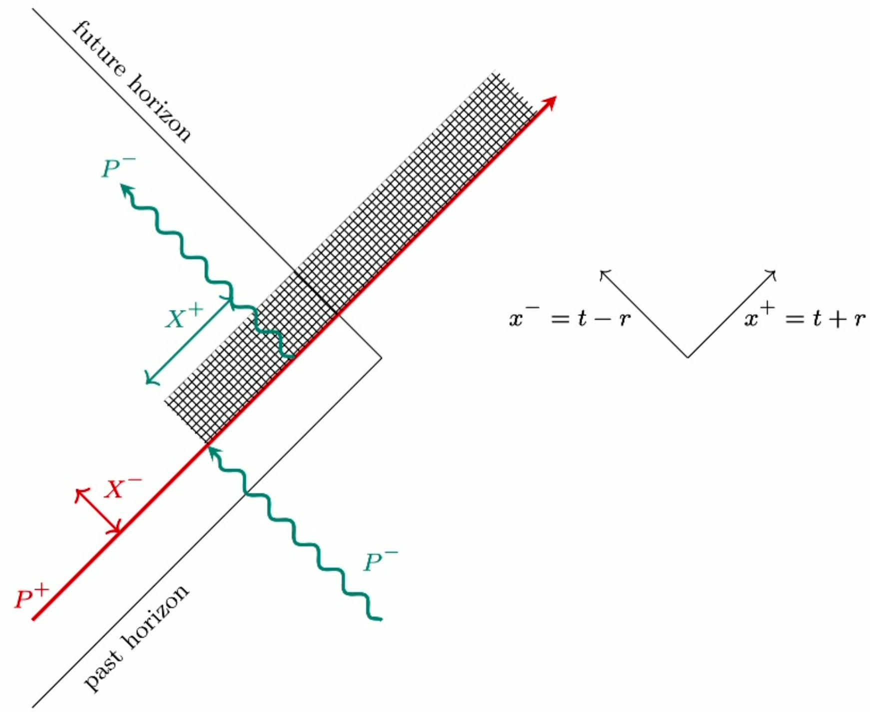


Laboratory for Quantum Fluctuations in Spacetime

Shockwaves and the 't Hooft Commutation Relations

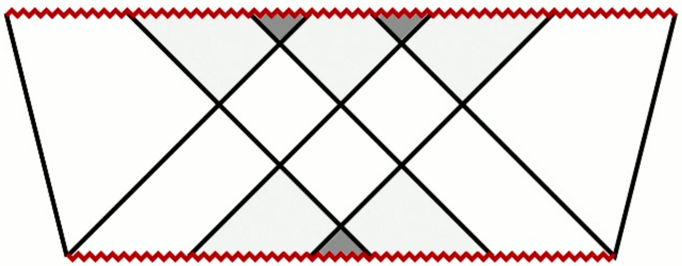
- Quantum mechanically, 't Hooft argued there is an inherent uncertainty between the locations of ingoing and outgoing modes of Hawking particles

$$[P_{-}(z,\bar{z}), X^{-}(z',\bar{z}')] = -i\gamma^{z\bar{z}}\delta^{(2)}(z-z')$$

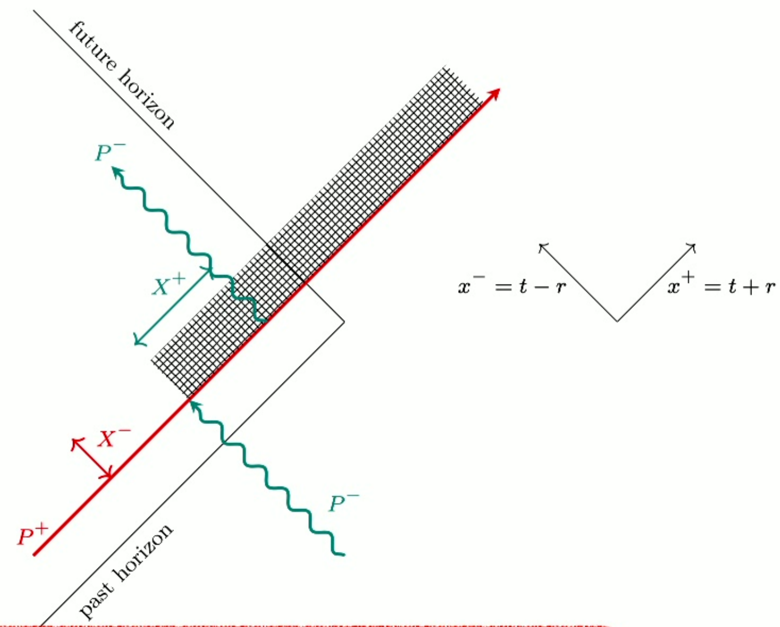


Shockwaves from Vacuum Fluctuations

Shockwaves cause shifts in the trajectories of particles



Multiple shocks



$$[X^+(z,\bar{z}), X^-(z',\bar{z}')] = 8\pi i G_N G(z - z')$$

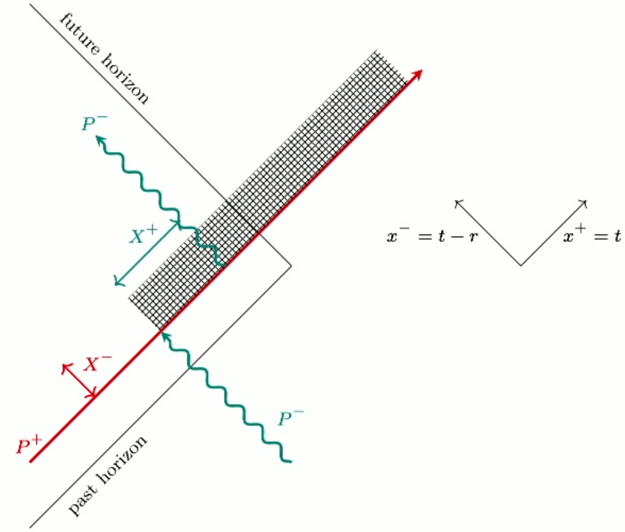
Minimum Uncertainty State

Euclidean Signature

$$\langle X^+(y) X^-(y') \rangle = 8\pi G_N G(y - y')$$

Shockwave Effective Action

Reproduces Einstein Equation



- Shockwave action (Verlinde's '93):

$$I = \int d^{d-2}y \left[-\frac{1}{\ell_p^{d-2}} \int d\tau \; X^u \Delta_y \frac{dX^v}{d\tau} + \int d\tau \left(X^u T_{u\tau} + X^v T_{v\tau} \right) \right]$$

- Gives same EOM as directly derived from EE:

$$T_{++} = \frac{1}{8\pi G_N} \Delta_y \frac{dX^-}{dx^+}$$

- On-shell:

$$I_{\text{horizon}} = -\frac{1}{8\pi G_N} \int d^2y X^+(y) \Delta_y X^-(y)$$

Quantum Mechanics of Shockwave Operators

Shockwave Operators = Raising and Lowering Operators in Euclidean Signature

- Lorentzian Operators are Hermitian $X^{\pm}(z) = (X^{\pm}(z))^{\dagger}$

- Continue to Euclidean Signature $X^{\pm}(z) = R(z) \pm T(z)$

$$T \to iT_E \qquad X^{\pm}(z) = -(X^{\mp}(z))^{\dagger}$$

- Euclidean Shockwave Operators are Now Raising and Lowering Operators

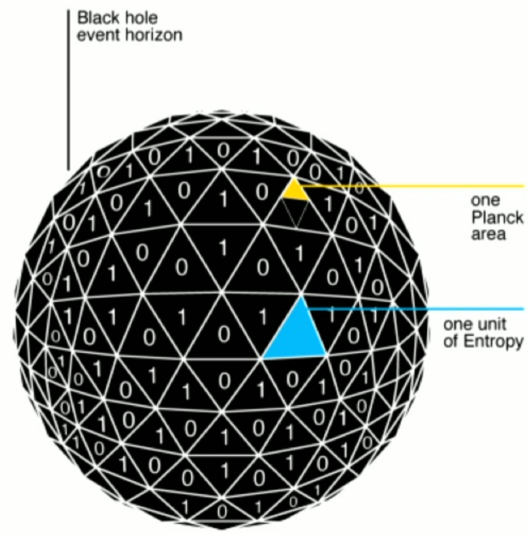
$$\langle 0|X_E^{-}(z) = 0 \qquad X_E^{+}(z)|0\rangle = 0$$

$$\langle X^+(y)X^-(y')\rangle = 8\pi G_N G(y-y')$$

Evaluate <K> as a Quantum Operator

$$K = \frac{1}{8\pi G_N}\int d^2y \lim_{y\to y'} \nabla_y \nabla_{y'} X^+(y)X^-(y')$$

- UV Divergence — regularized by fundamental physics scale
- "Pixels" on horizon set fundamental length scale



$$\lim_{y'\to y} \nabla_y \nabla_{y'} G(y-y') \sim \frac{1}{\ell_p^2}$$

$$\Rightarrow \quad \langle K\rangle = \frac{Area}{4G}$$

- Reminiscent of UV divergence that appears in calculations of entanglement entropy

Modular Fluctuations

UV Divergence — regularized by fundamental physics scale

- Assume fluctuations are Gaussian so that 4-pt decomposes into product of 2-pt's

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

$$= \frac{1}{(8\pi G_N)^2} \int d^2y \int d^2y' \nabla_y \nabla_{y'} \langle X^+(y) X^-(y') \rangle \nabla_y \nabla_{y'} \langle X^+(y') X^-(y) \rangle$$

➡ $$\langle \Delta K^2 \rangle = \frac{Area}{4G}$$

$$\langle K \rangle = S_{\text{ent}} = \langle \Delta K^2 \rangle = \frac{A(\Sigma)}{4G_N}$$

From Gravitational Memory to Shockwaves

't Hooft commutation relations are gauge equivalent to commutation relations appearing in celestial holography

Part II.

He, Raclariu, KZ 2305.14411, WIP

Laboratory for Quantum Fluctuations in Spacetime

Shockwaves and soft commutators

- Goal: Show 't Hooft commutation relation is equivalent to canonical commutation relations of soft modes in 4-d AFS
- Show this via a diffeomorphism between shock and memory metrics

$$\{C_{\bar{z}\bar{z}}(u, z, \bar{z}), N_{ww}(u', w, \bar{w})\} = 16\pi G_N \gamma_{z\bar{z}} \delta(u - u') \delta^{(2)}(z - w)$$

"Goldstone mode" "Soft mode"

Shockwave and Memory Metrics

Lightning Review

- Shockwave metric:

$$ds^2 = -du^2 - 2du\,dr + 2r^2\gamma_{z\bar{z}}dz\,d\bar{z} + \underbrace{\alpha(z,\bar{z})\delta(u-u_0)}_{h_{uu}}du^2 \;+\ldots$$

- Memory Metric in Bondi gauge:

$$N_{zz}(u,z,\bar{z}) = \partial_u C_{zz}(u,z,\bar{z})$$

$$\begin{aligned} ds^2 = &-du^2 - 2\,du\,dr + 2r^2\gamma_{z\bar{z}}\,dz\,d\bar{z} \\ &+ \left(rC_{zz}(u,z,\bar{z})\,dz^2 + D^z C_{zz}(u,z,\bar{z})\,\overbrace{du}\,dz + \text{c.c.}\right) \\ &+ N(z,\bar{z})\delta(u-u_0)\,du\,dr + \left(r\partial_z N(z,\bar{z})\delta(u-u_0)\,du\,dz + \text{c.c.}\right) \end{aligned}$$

Gravitational Memory

Relation between shockwaves and memory

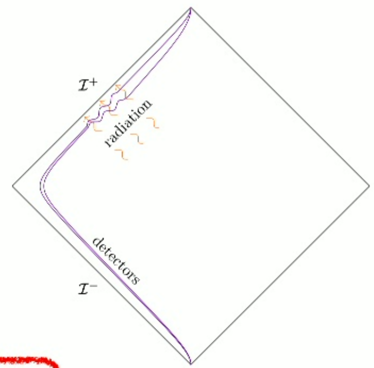
- Gravitational radiation, characterized by the news N, causes a change in the shear C

$$T_{uu} \propto \delta(u - u_0)$$

$$C_{zz}(u, z, \bar{z}) = D_z^2 N(z, \bar{z})\Theta(u - u_0) - 2D_z^2 C(z, \bar{z})$$

$$\uparrow$$

$$C_{zz}^{\text{vac}}(z, \bar{z})$$



- Already suggests

Shockwave	Memory
Momenta P	News N
Light Ray Shifts X	Shear C

The Diffeomorphism

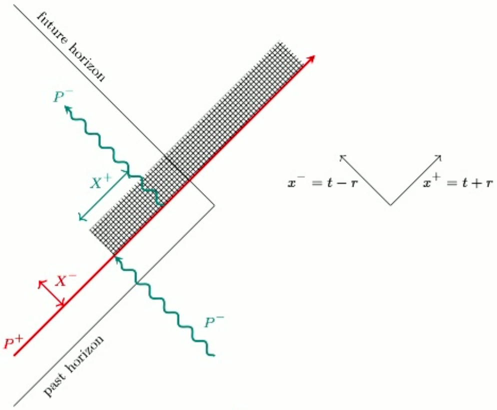
Preserve Bondi Gauge

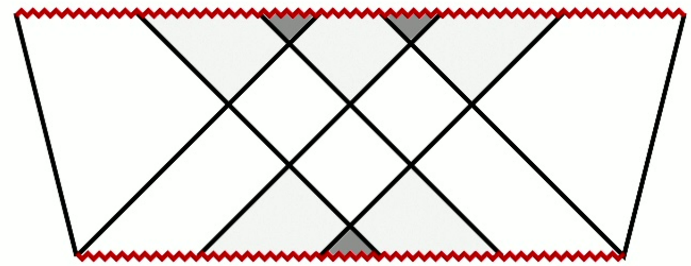
- After performing the diffeomorphism, one finds the two metrics are related by

$$-\frac{1}{2}(\Box + 2)N(z,\bar{z}) = \alpha(z,\bar{z}) \quad \Rightarrow \quad P_{-}(z,\bar{z}) = \frac{1}{32\pi G_N}\Box(\Box + 2)N(z,\bar{z})$$

- Coordinate shift under super translation

$$x^{-} \to x^{-} - C \quad \Rightarrow \quad X^{-}(z,\bar{z}) = -C(z,\bar{z})$$

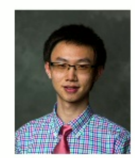




Accumulation into the Infrared

Does a photon trajectory remember the effects of multiple quantum shocks?


Part III.



Bak, Keeler, Zhang, KZ 2403.18013

Zhang, KZ 2304.12349

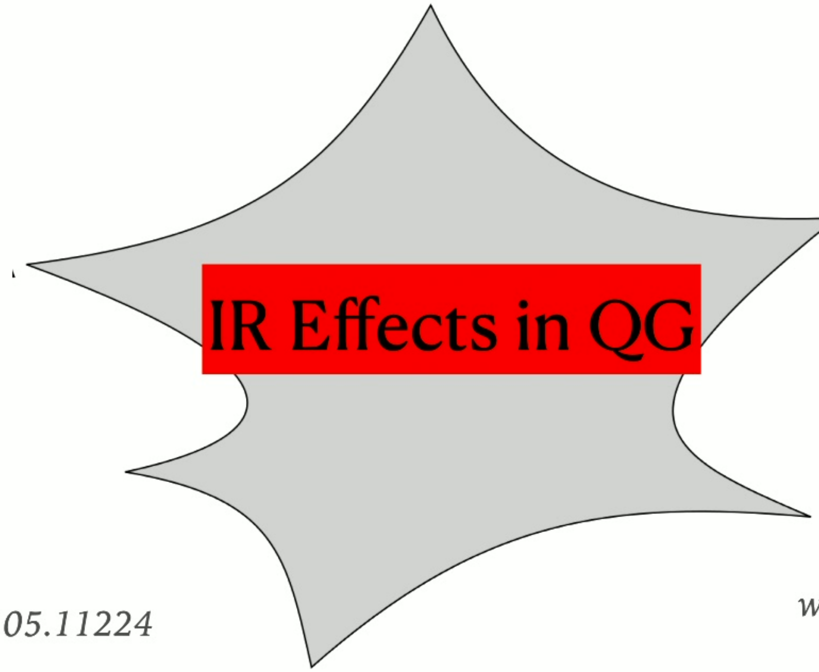
Summary

Towards Flat Space Holography

- 't Hooft commutation relations developed in the context of black hole horizons, when suitably applied to light-sheet horizons, are equivalent to soft commutation relations
- Those commutation relations, suitably regulated, give rise to $\langle K \rangle = S_{\rm ent} = \langle \Delta K^2 \rangle = \frac{A(\Sigma)}{4G_N}$ previously derived only in AdS/CFT. Suggests Universality.
- If we take these commutation relations seriously, and apply a memory effect that allows them to accumulate, we get potentially observable fluctuations in the photon round-trip time in an interferometer. These signatures are being studied in more detail.

One Coin, Many Faces

Connecting equivalent physical descriptions



A. AdS/CFT

w/Verlinde 1911.02018

B. Light Ray Operators

w/Verlinde, 2208.01059

C. "Pixellon"

KZ 2012.05870
w/Lee,Li,Chen 2209.07543
w/Bub, Du, Li, Zhang, Chen 2305.11224

D. Gravitational effective action / saddle point expansion

w/Banks, 2108.04806

E. Shockwaves and Gravitational Memory

w/He, Raclariu 2305.14411

F. Hydrodynamics EFT

w/Zhang 2304.12349
w/Bak, Keeler, Zurek 2403.18013

G. Soft Effective Action and Wilson Lines

w/He, Mitra, Sivaramakrishnan 2403.14502

H. 2-d Models, e.g. JT gravity

w/Gukov, Lee 2205.02233
w/Bub, He, Mitra, Zhang WIP