New Approaches in Flat Space Holography and Observational Signatures

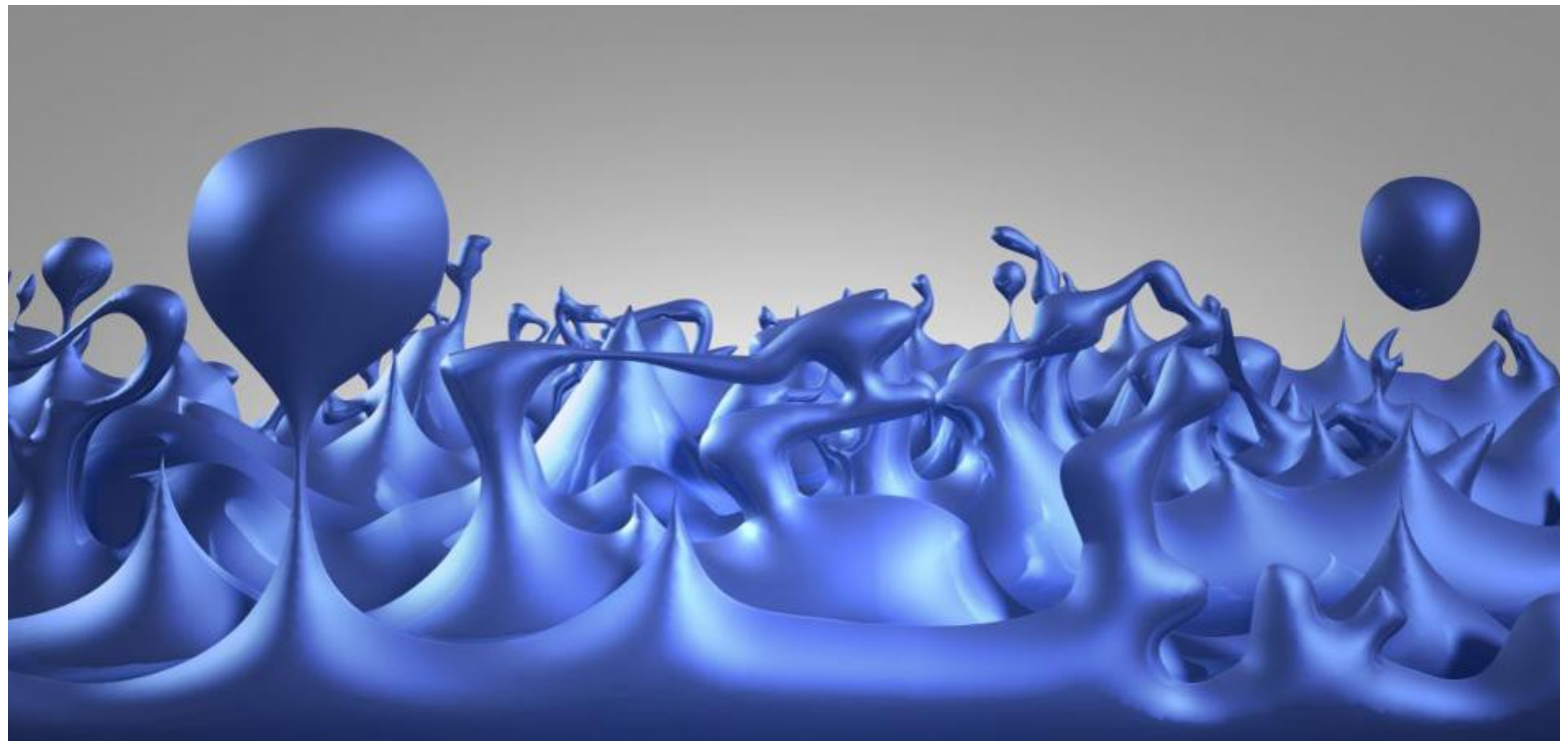
Summary: 2205.01799
Work with:
Verlinde 1902.08207, 1911.02018, 2208.01059
KZ 2012.05870
Banks 2108.04806
Gukov, Lee, 2205.02233
Li, Lee, Chen 2209.07543
He, Raclariu, 2305.14411
Zhang 2304.12349

Kathryn Zurek

Motivation: Understanding Spacetime Fluctuations

And Possible Observational Signatures

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



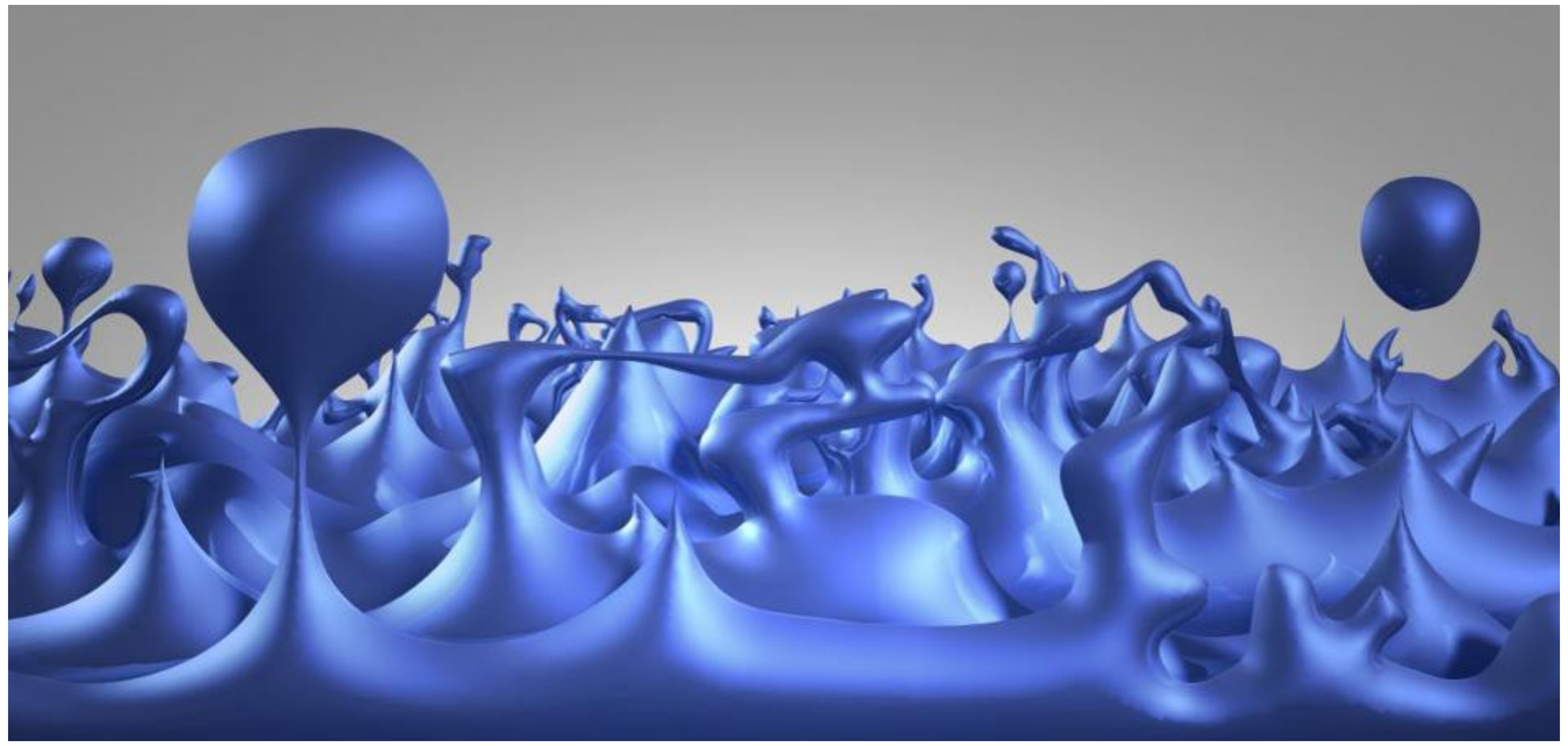
$$l_p \sim 10^{-35}\ \mathrm{m} \sim 10^{-43}\ \mathrm{s}$$

Motivation: Understanding Spacetime Fluctuations

And Possible Observational Signatures

- New view: Entanglement, non-local and infrared effects are now broadly understood to be important

Studied extensively in context of BH



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

- Naive EFT seems to break down

UV effects may not decouple in IR

Thermodynamics of Black Holes

Entropy and Information in Black Holes

Entropy of a Black Hole

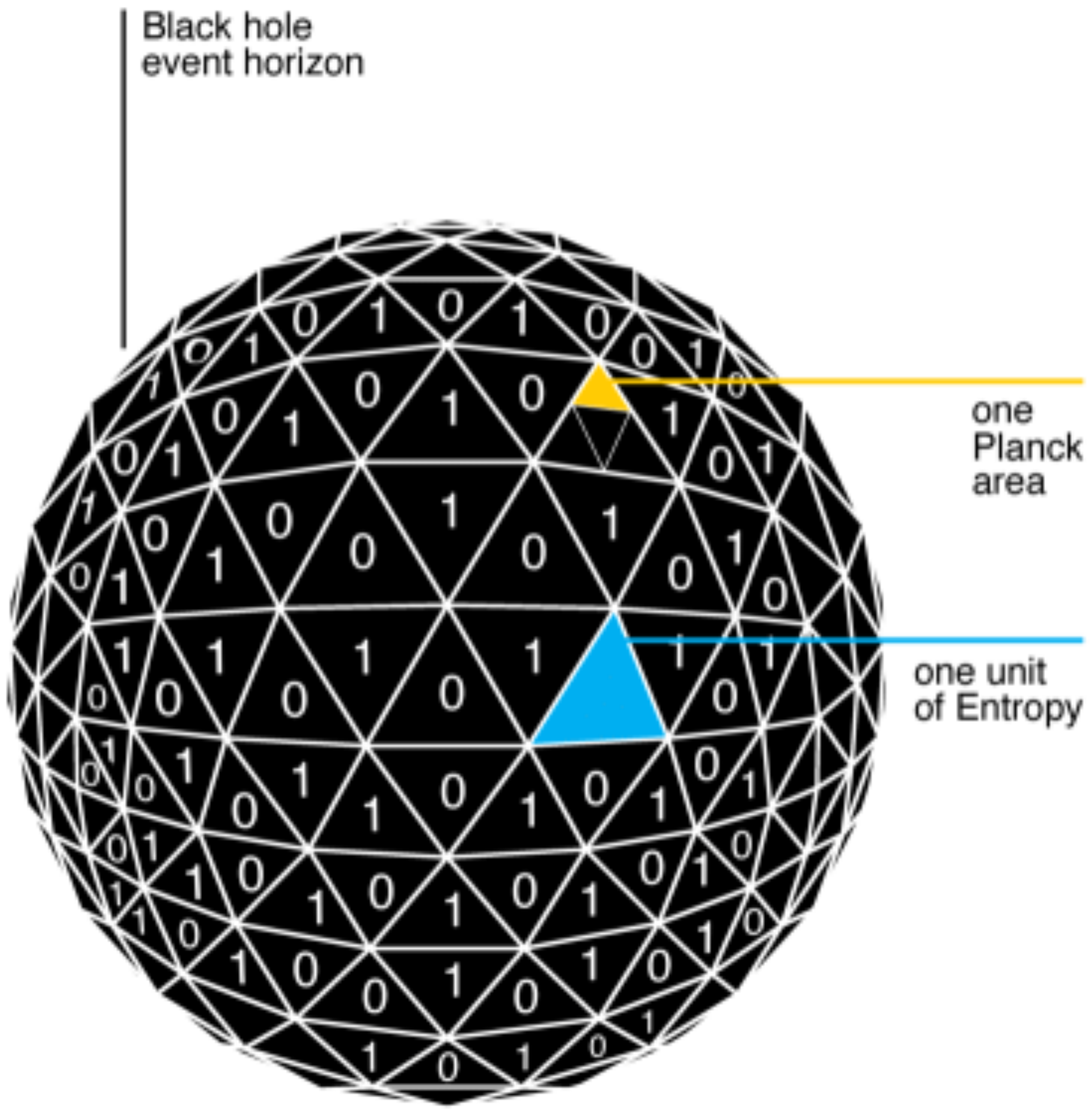
=

Area of its Horizon

Entropy is **Information**

it counts the number of bits

$$S = \frac{Area}{4\ell_p^2}$$



Quantum Fuzziness

At black hole horizons

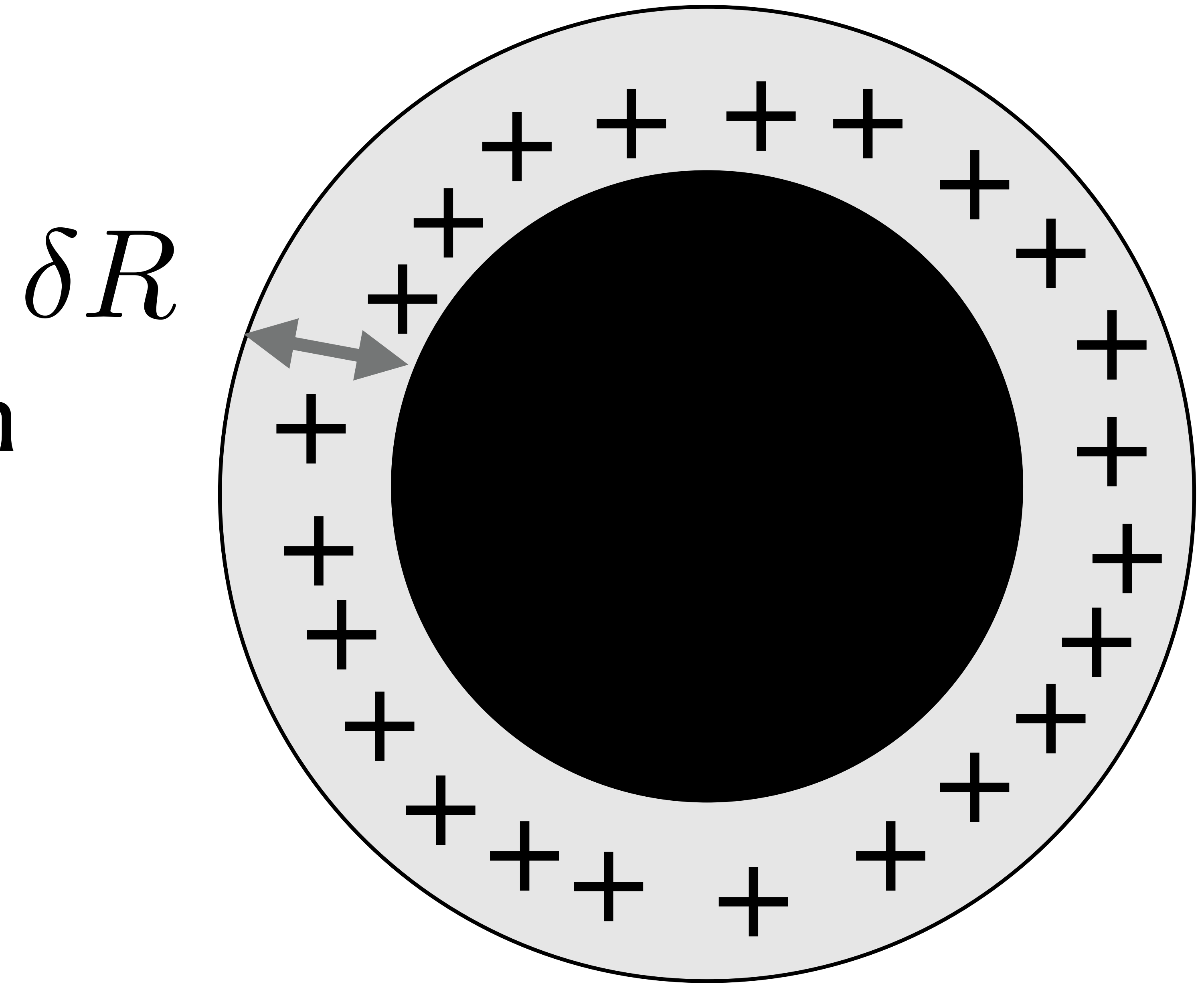
- Degrees of freedom PIXELS can fluctuate thermodynamically

$$S = \frac{A}{4G} \qquad T \sim \frac{1}{R}$$

- Causes mass of black hole to fluctuate, which shifts horizon

$$\delta R \underset{d=4}{\sim} \sqrt{l_p R} \qquad \delta R^2 \sim \frac{R^2}{\sqrt{S_{\mathrm{BH}}}}$$

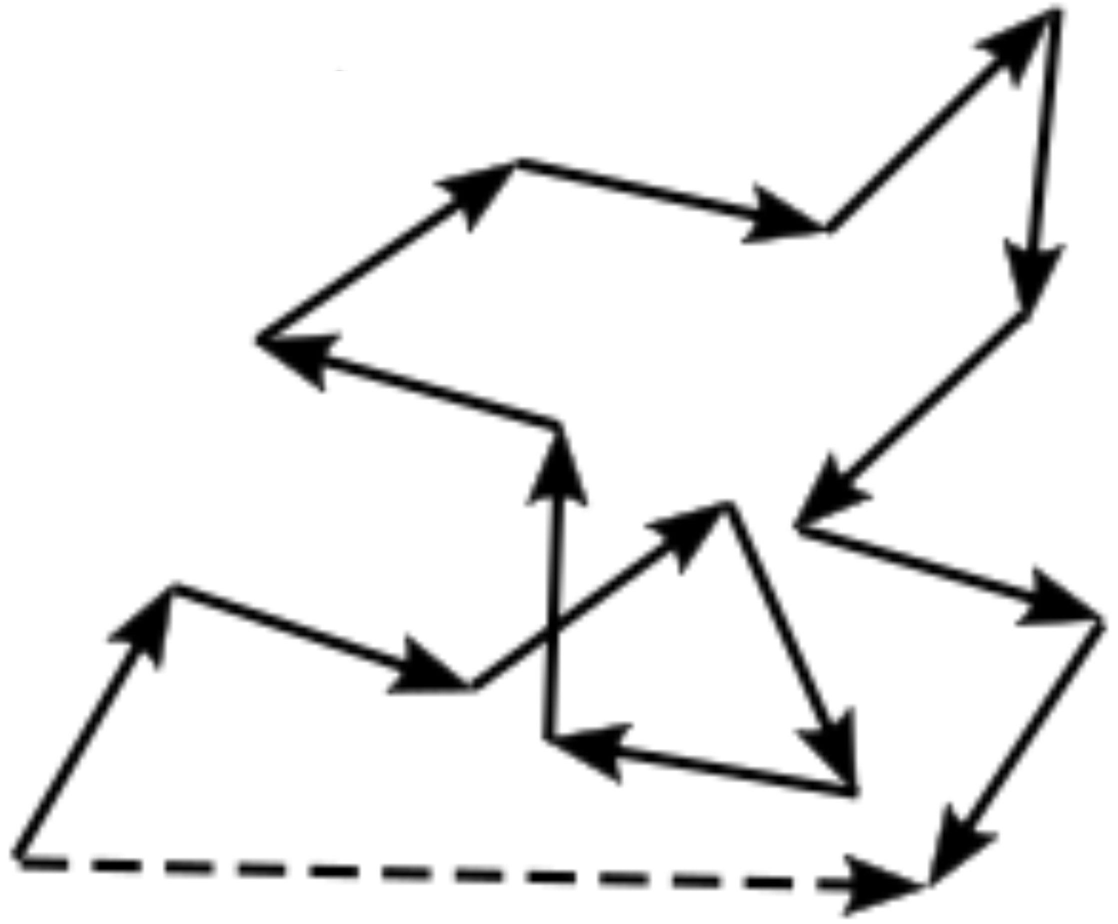
- Unobservably small in a black hole



Marolf 2003

Brownian Noise

UV effects can be transmuted in infrared



$$\Delta t = R/v$$

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

$D \sim \Delta t$ — UV Scale

Observing Time — IR Scale

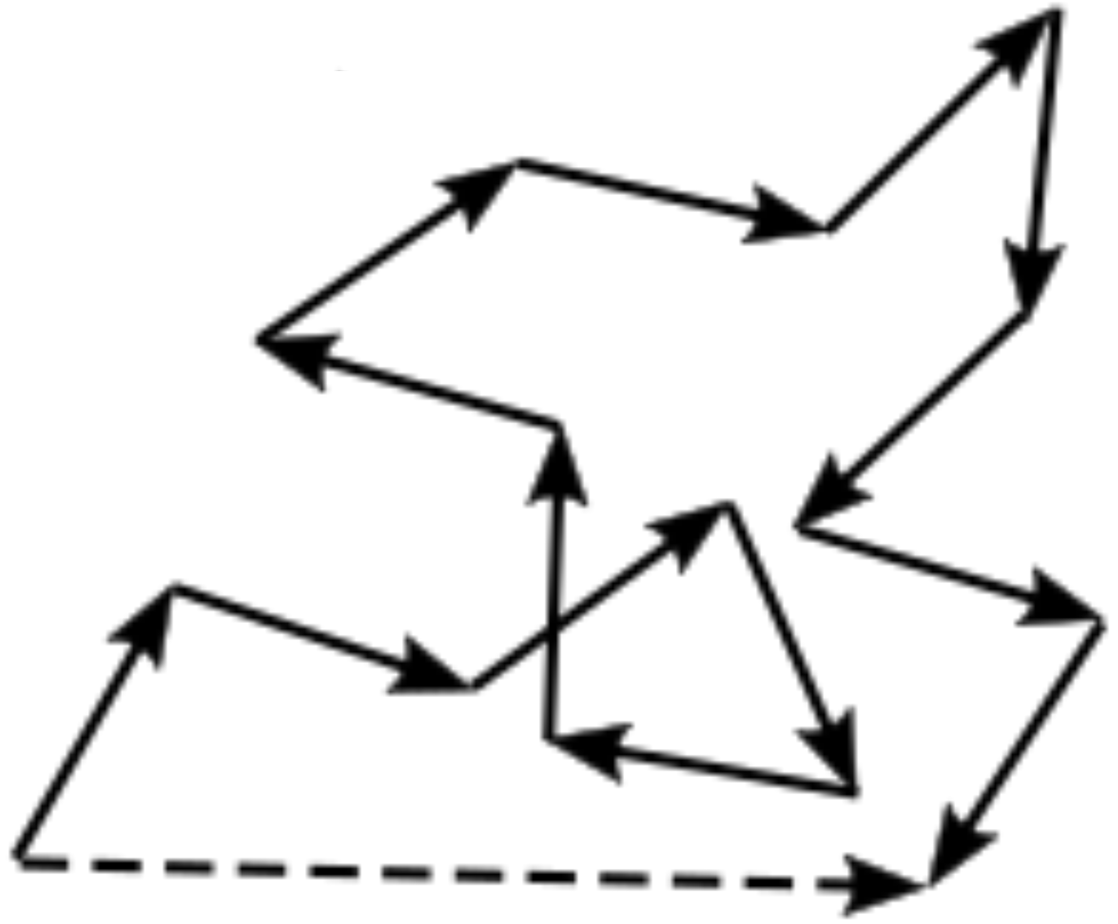
Brownian Noise

UV effects can be transmuted in infrared

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

UV Scale

IR Scale



$$\Delta t = R/v$$

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

$D \sim \Delta t$

UV Scale

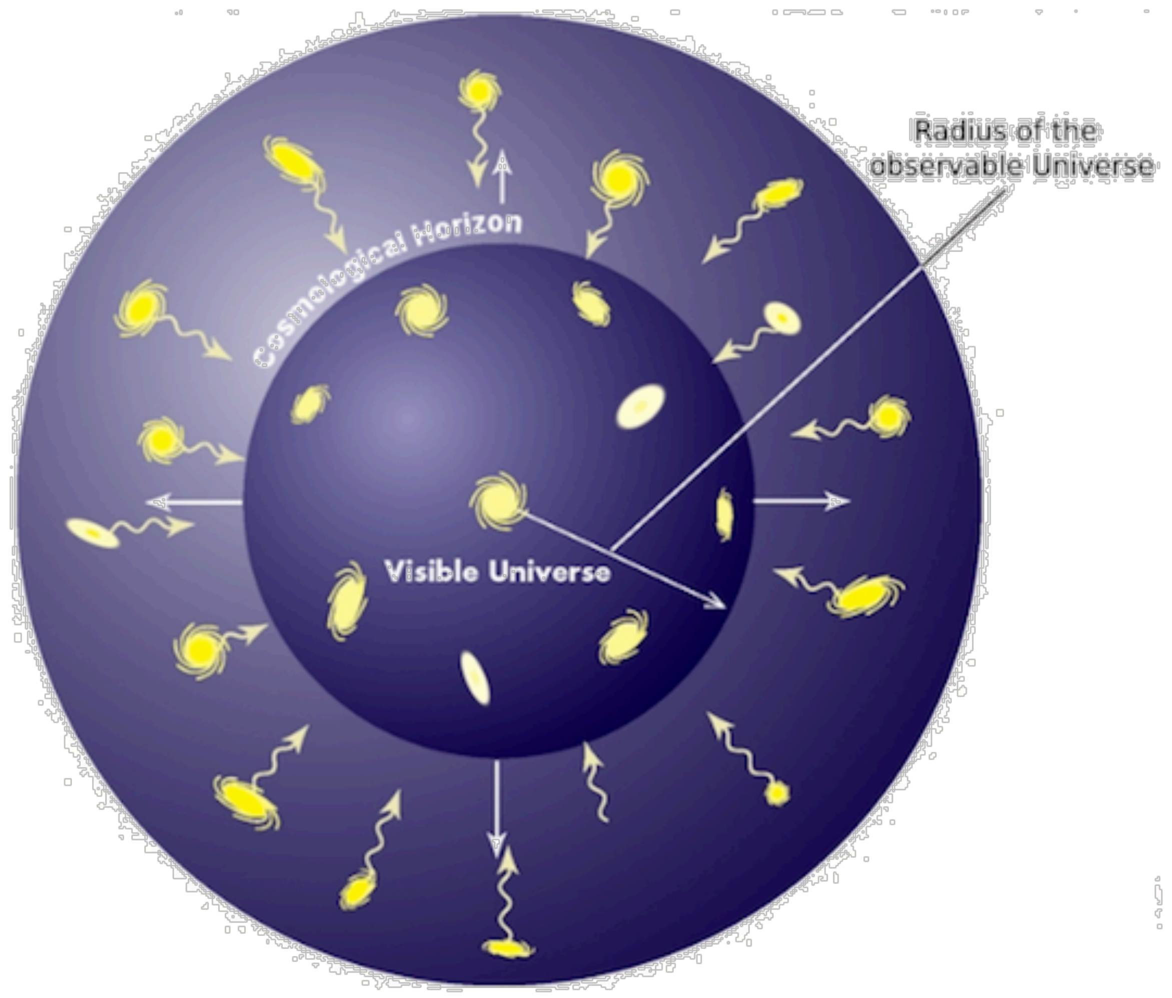
Observing Time

IR Scale

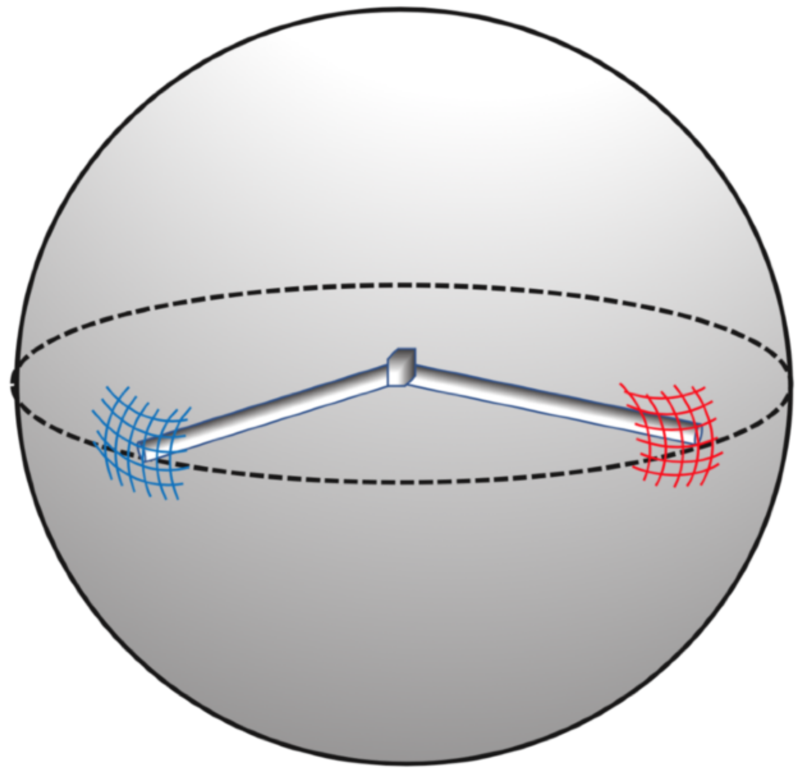
The World as a Hologram

Certain Physics at Horizons has Universal Characteristics

Black Hole Horizon



Cosmological Horizon



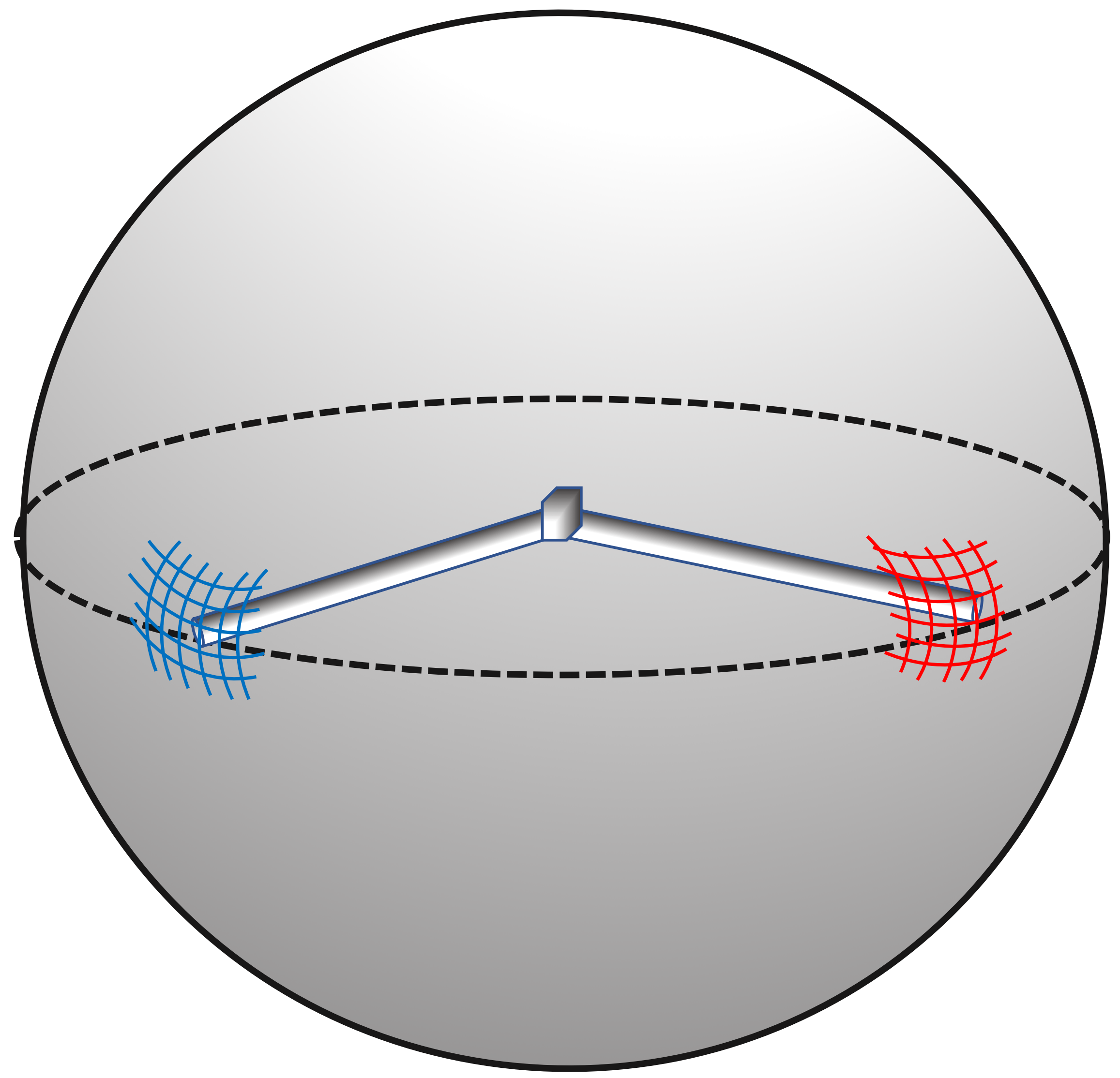
Flat Space Horizon

The information of quantum gravity is encapsulated in the number of degrees of freedom on the Area bounding a volume

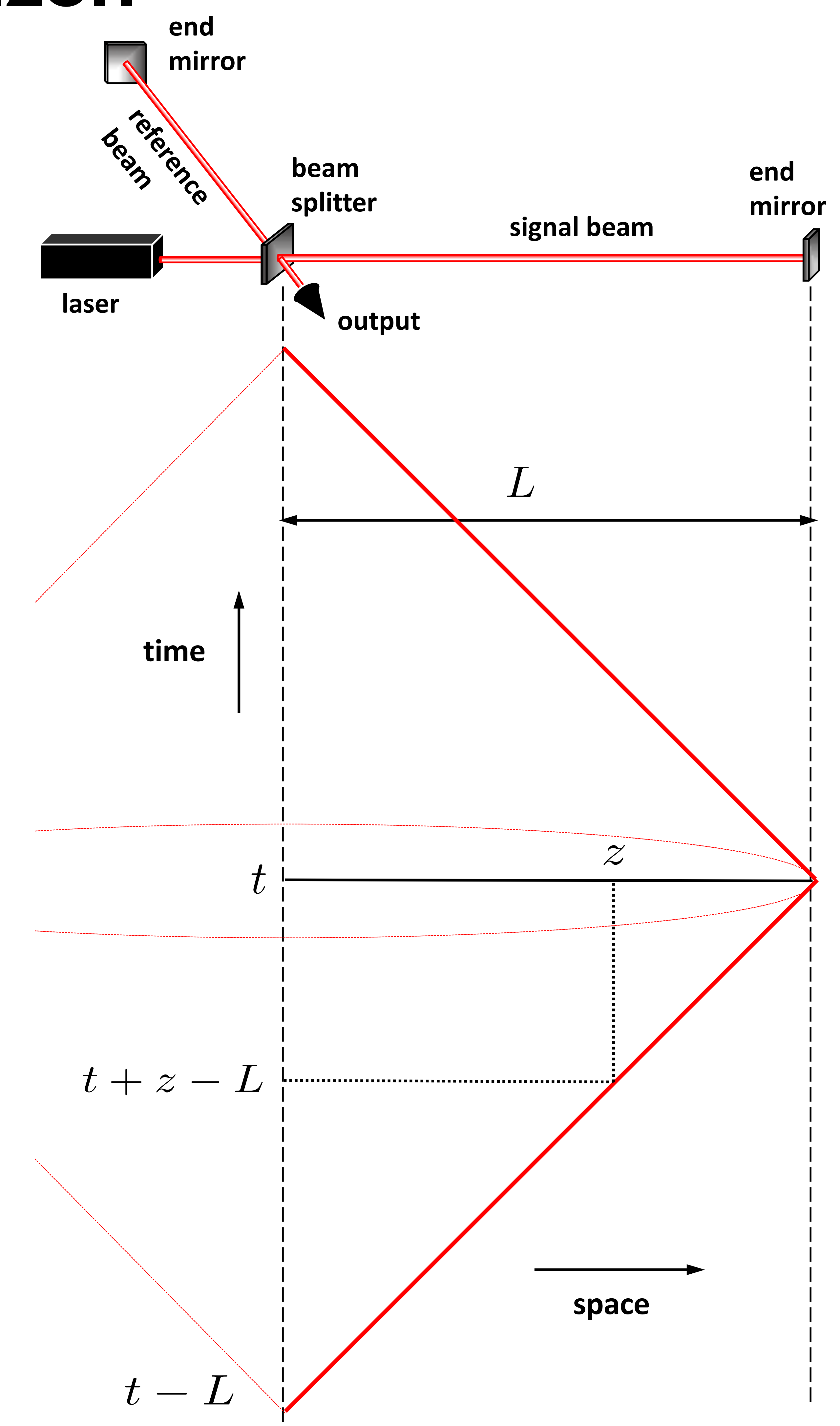
Why would flat empty space have the same uncertainty as a (quantum) black hole?

An Experimental Measurement Defines a Horizon

- Some horizon features are Universal



- Whether black hole, cosmological or light sheet



Black Hole - (Empty!) Causal Diamond Dictionary

Mapping is precise in certain contexts (such as AdS/CFT)

Black Hole

- Horizon
- Black Hole Temperature
- Black Hole Mass
- Thermodynamic Free Energy
- Thermodynamic Entropy

Causal Diamond

- Horizon defined by null rays
- Size of Causal Diamond

$$T \sim 1/L$$

- Modular Fluctuation

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

- Partition Function

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

- Entanglement Entropy

$$S = \langle K \rangle = \frac{A}{4G}$$

Black Holes Vs. Flat Empty Space

The Topological Black Hole

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

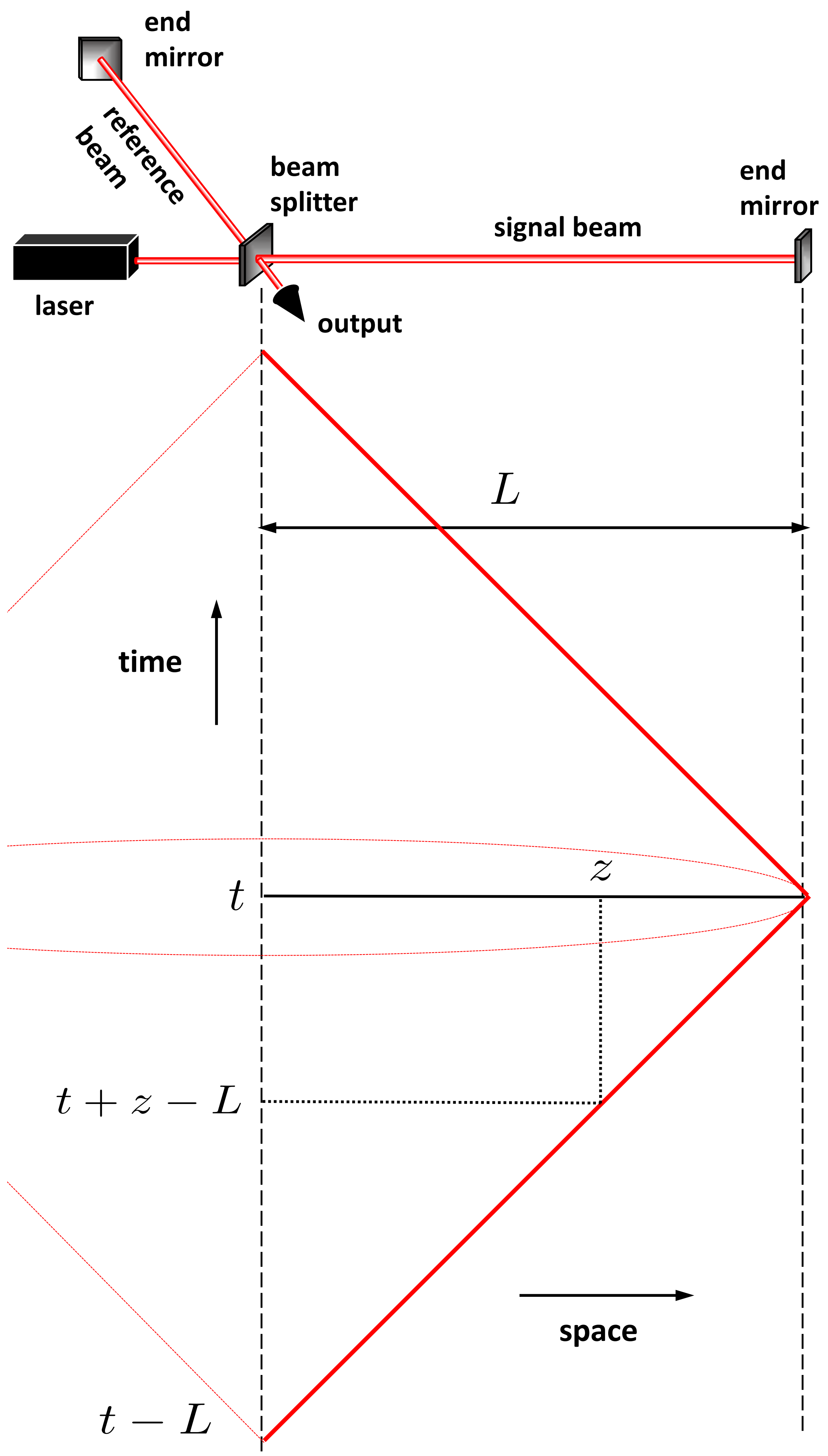
- As long as we are interested in only the part of spacetime inside the causal diamond, the metric in some common spacetimes can be mapped to "topological black hole"

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

$$\Downarrow$$

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

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



Our Argument: Calculate Vacuum Fluctuation

Step 1

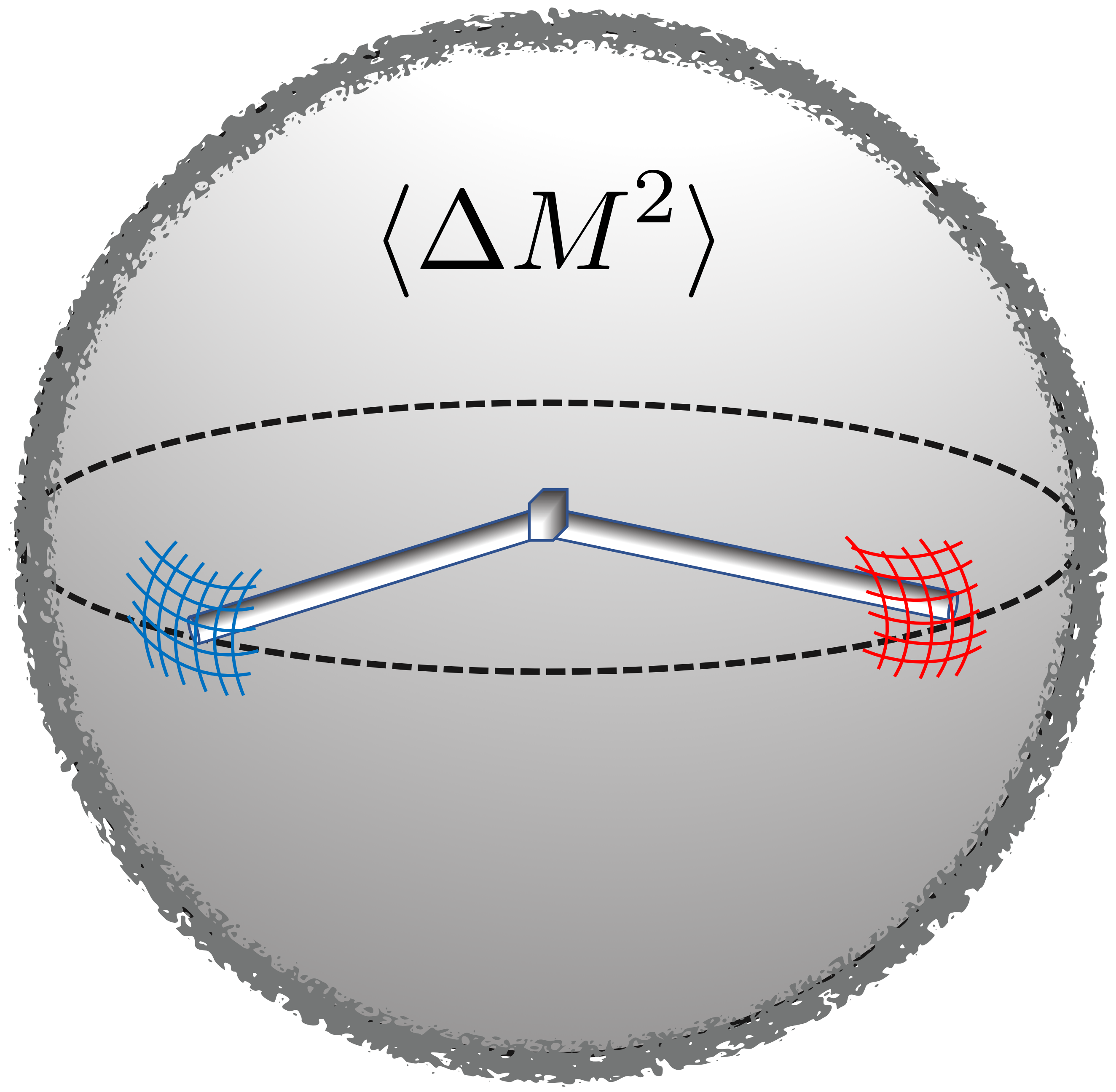
- Number of holographic degrees of freedom is the entropy

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

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

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

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



Our Argument: Vacuum Fluctuation Sources Metric Fluctuation

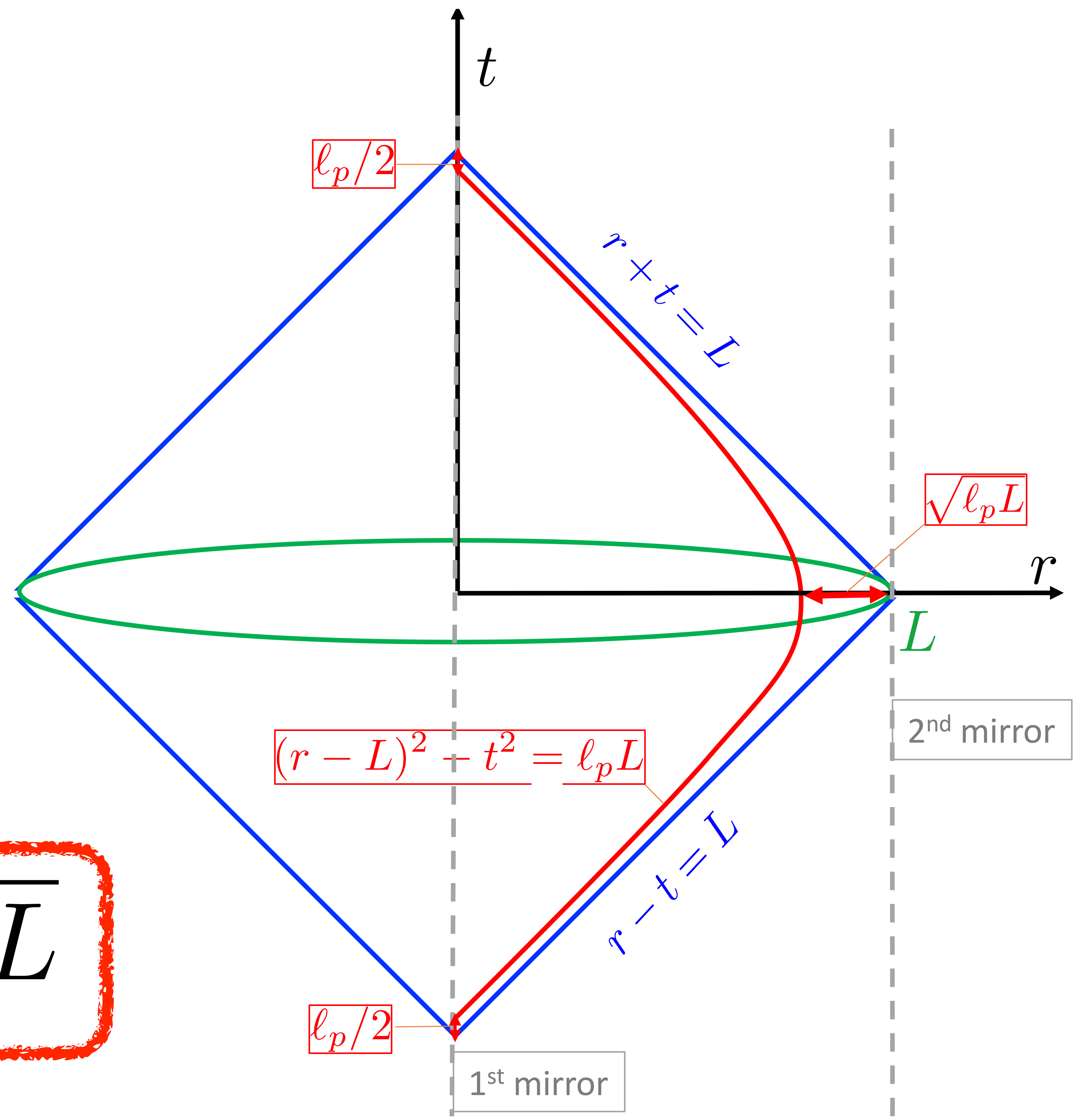
Step 2

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

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

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

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



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 fluctuations?

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

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

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

What can we test in interferometers?

1. Fundamental Uncertainty in Light Ray Operators

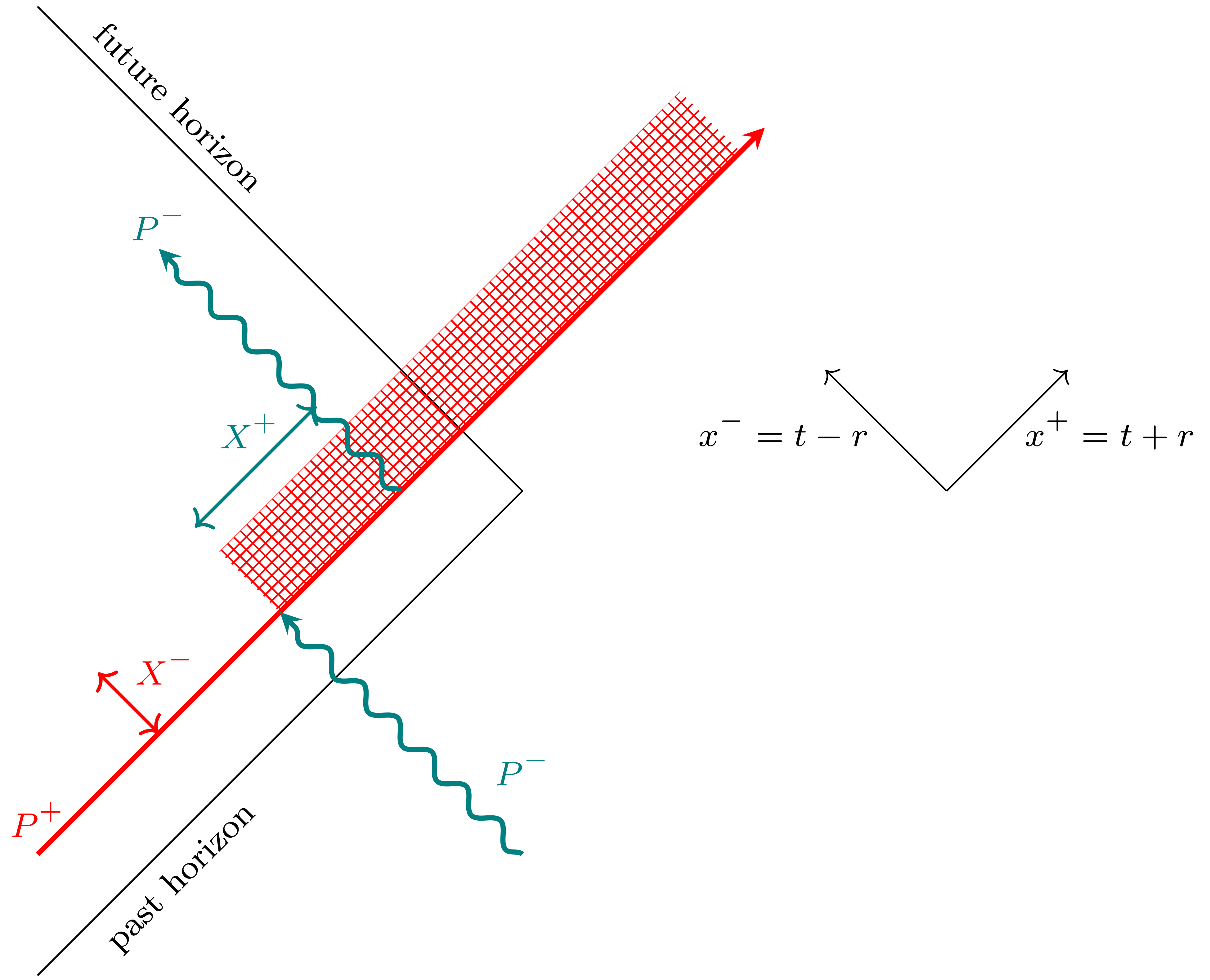
$$X^v(y) = \tilde{\ell}_p^2 \int_{-L}^{L} du \int d^{d-2}y' f(y,y')\, T_{uu}(u,y')$$

$$X^u(y) = \tilde{\ell}_p^2 \int_{-L}^{L} dv \int d^{d-2}y' f(y,y')\, T_{vv}(v,y').$$

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

Modular Hamiltonian is shockwave on-shell action!

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



w/Verlinde 2208.01059

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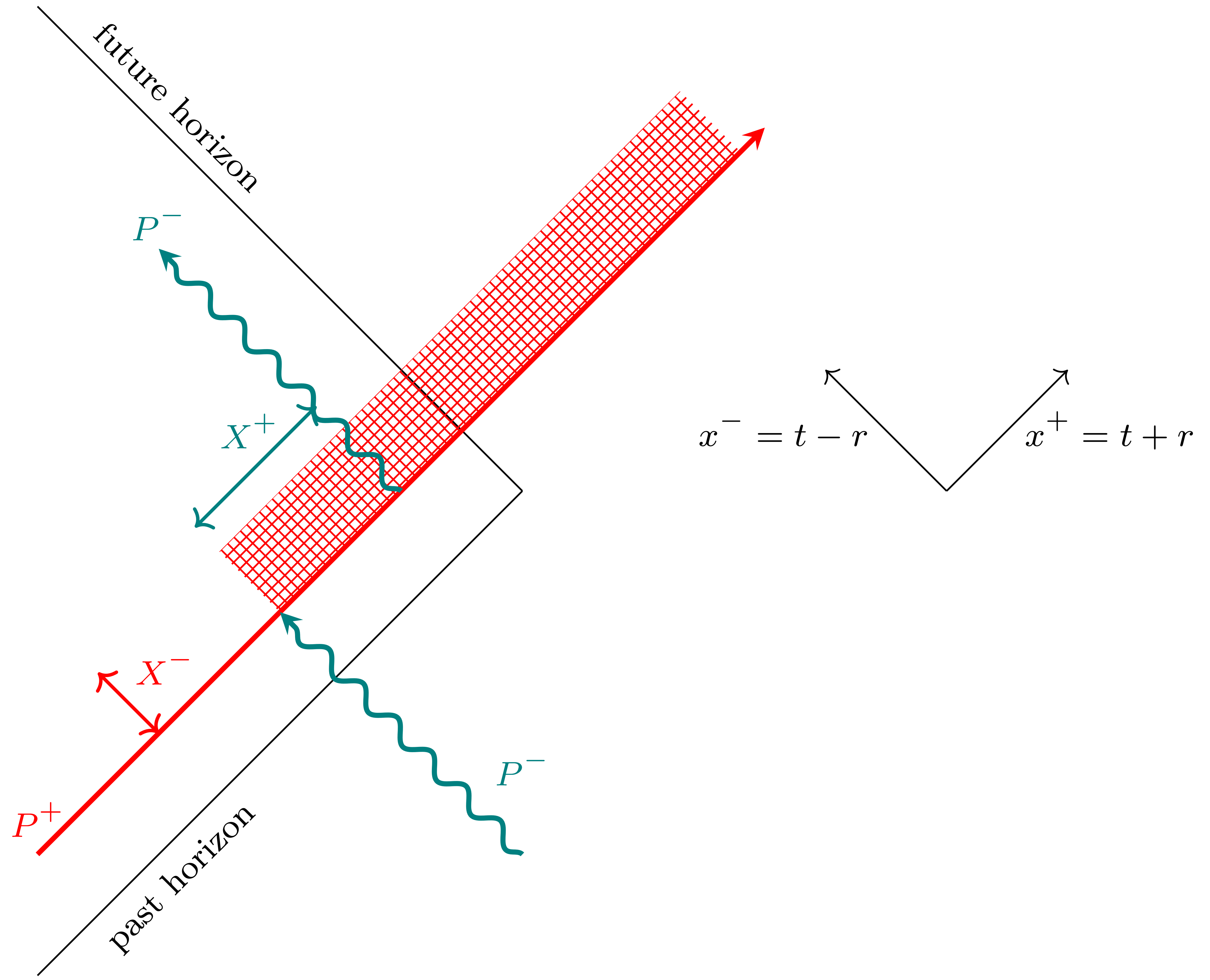

$$\Rightarrow \quad \langle K \rangle = S_{\text{ent}} = \langle \Delta K^2 \rangle = \frac{A(\Sigma)}{4G_N}$$

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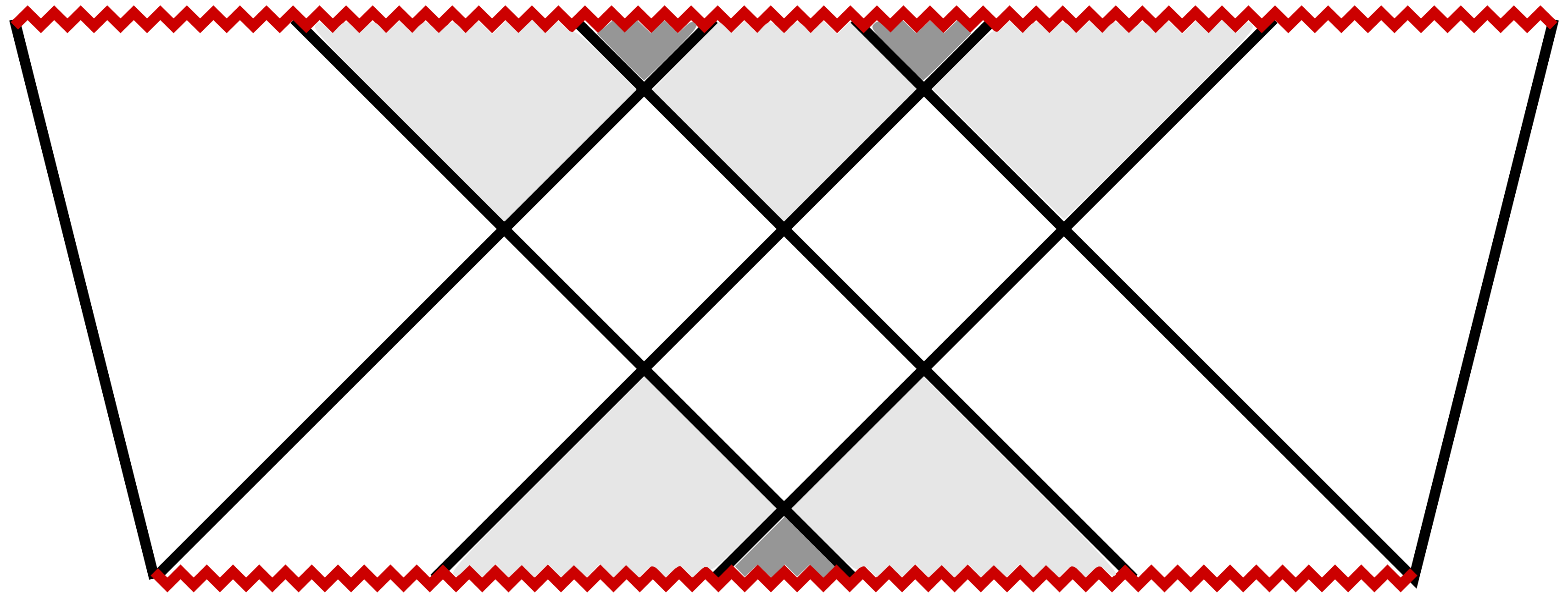
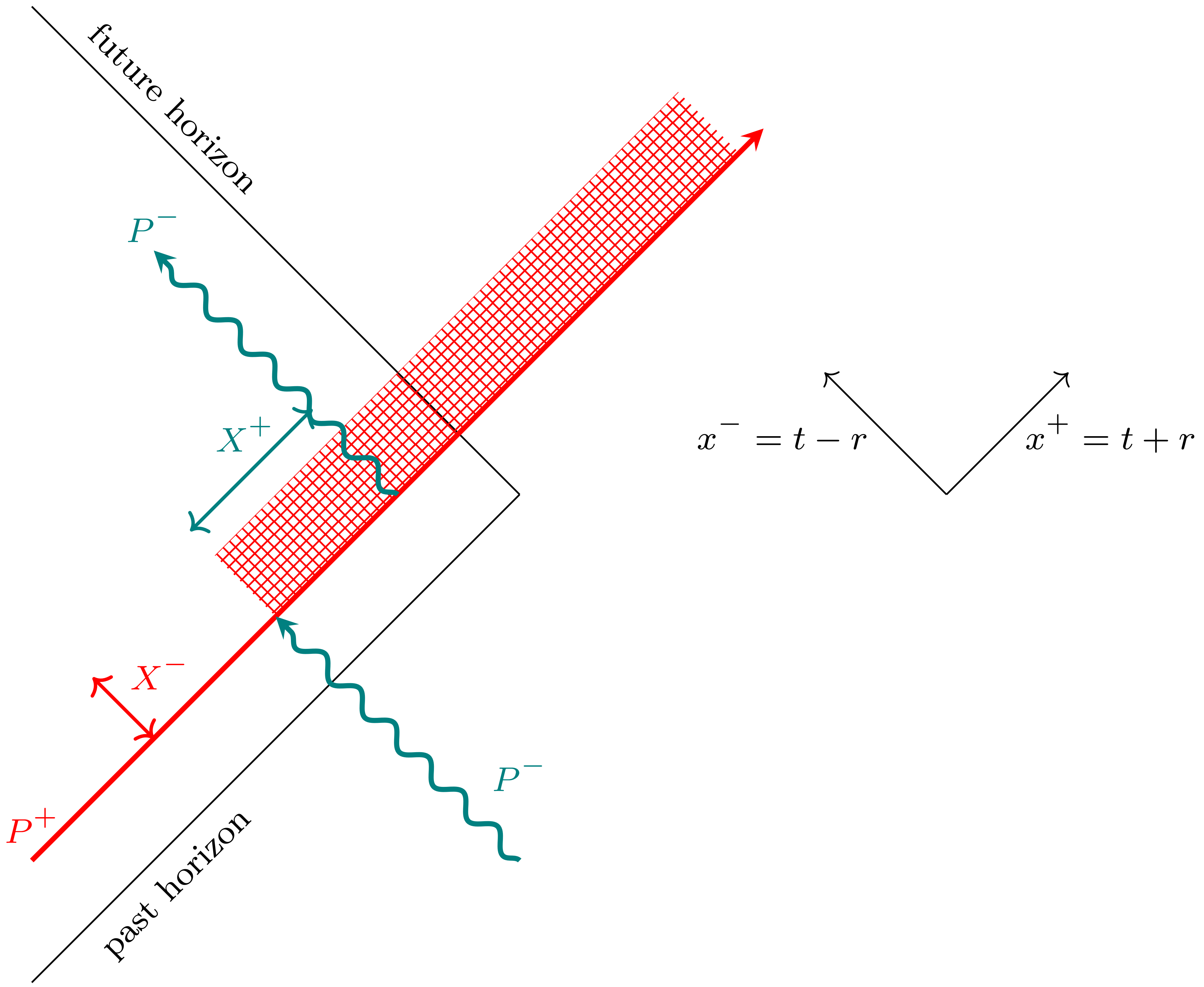
What can we test in interferometers?

2. Accumulation/Memory into the infrared...



$$\langle X^u(\Omega) X^v(\Omega') \rangle = \tilde{l}_p^{\,2} f(\Omega, \Omega')$$

Multiple shocks



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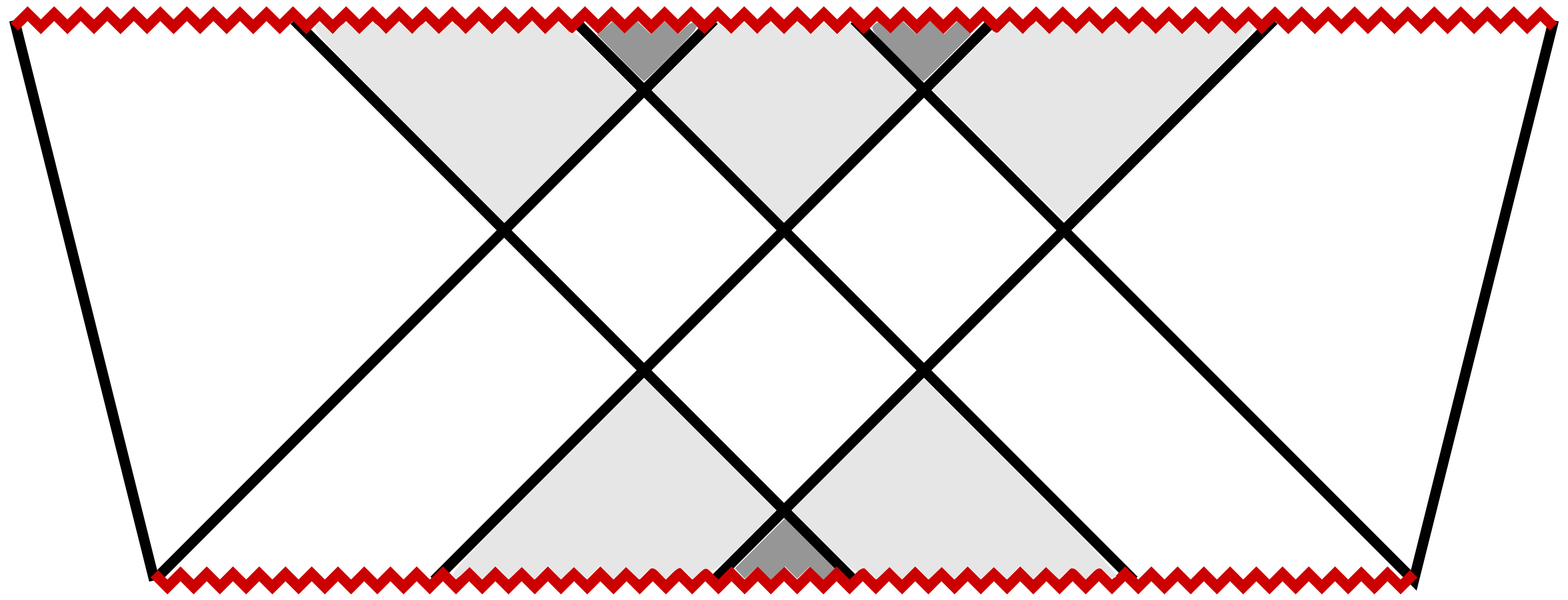

$$\langle X^u(\Omega) X^v(\Omega')\rangle = \tilde{l}_p^{\,2} f(\Omega, \Omega')$$

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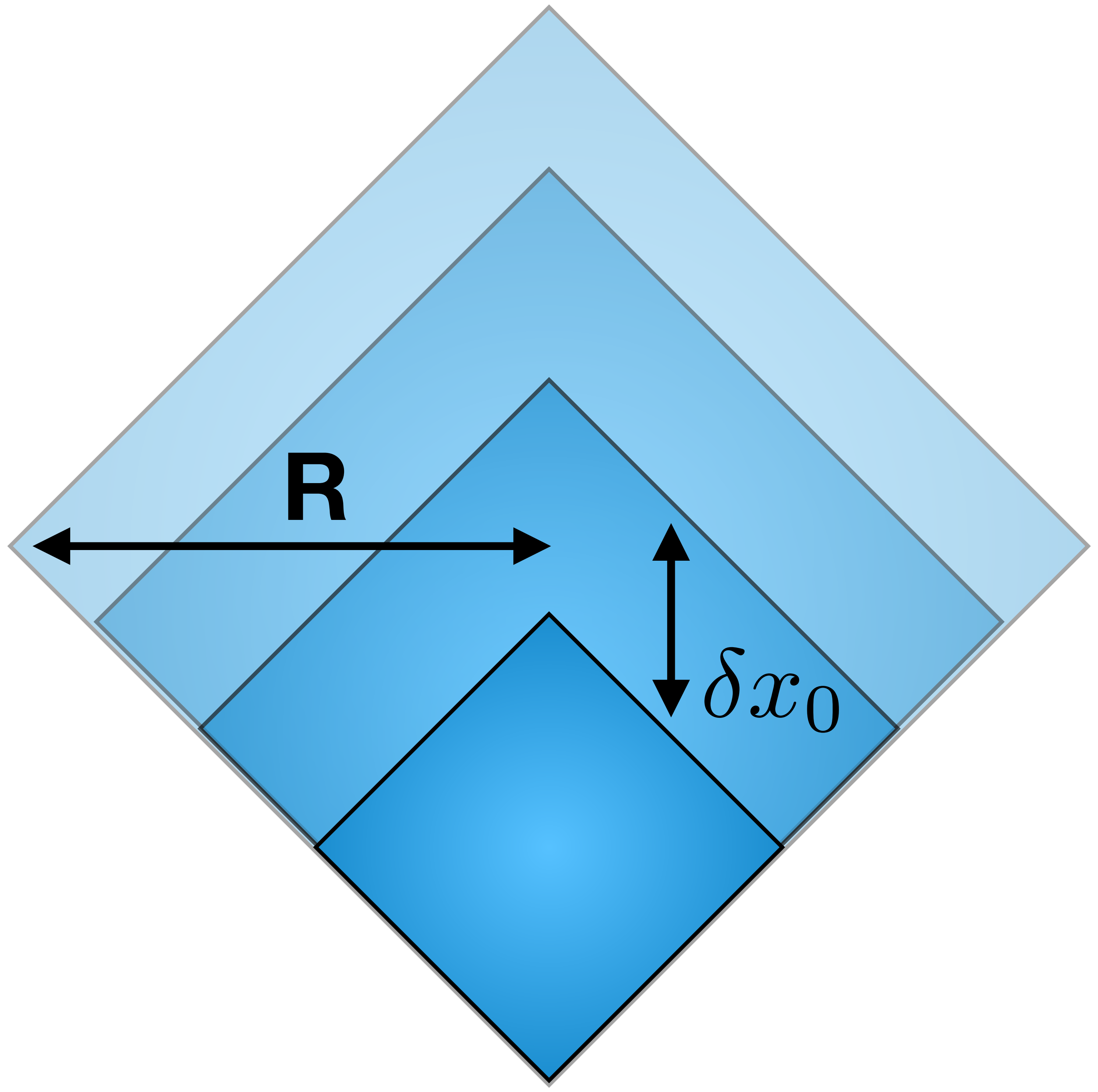


$$\delta L \sim \sqrt{l_p L}$$

d=4

w/Banks 2108.04806

Are these postulates reasonable?

For flat empty space

- First postulate can be derived from celestial "soft" commutation relations
  - Commutation relations appearing in celestial holography are gauge equivalent to 't Hooft commutation relations (w/He&Raclariu 2305.14411)

$$
\begin{aligned}
[P_-(z,\bar z), X^-(z',\bar z')] &= -\frac{1}{32\pi G_N}\Box_z(\Box_z+2)\big[N(z,\bar z), C(z',\bar z')\big] \\
&= -\frac{i}{4\pi}\Box_z(\Box_z+2)\big(S\log|z-z'|^2\big) \\
&= -i\gamma^{z\bar z}\delta^{(2)}(z-z')\,.
\end{aligned}
$$

  - 't Hooft commutation relations imply modular relation (w/E.Verlinde 2208.01059)
- 't Hooft commutation relations gives rise to a quantum noise term that turns EE into hydro (w/Zhang 2304.12349) —> accumulation of fluctuations

Hydrodynamics of Spacetime

Connecting UV Physics to the Infrared

- Hydrodynamics has been studied extensively as an effective description of gravity
- i.e. Einstein Equation Reduces to a Navier-Stokes Equation

$$\left(\frac{d-2}{L^2} - \nabla_\perp^2\right) h_{uu} = 0$$

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

- With Quantum Source Zhang, KZ 2304.12349

Equivalent to 't Hooft commutation relation!

$$\left(\frac{d-2}{L^2} - \nabla_\perp^2\right) [h_{uu}(u, \mathbf{x}_\perp), h_{vv}(v, \mathbf{x}'_\perp)] = \frac{i}{2} \ell_p^{d-2} \delta(u-u_0)\delta(v-v_0)\delta^{d-2}(\mathbf{x}_\perp - \mathbf{x}'_\perp)$$

At a Light-Sheet Horizon

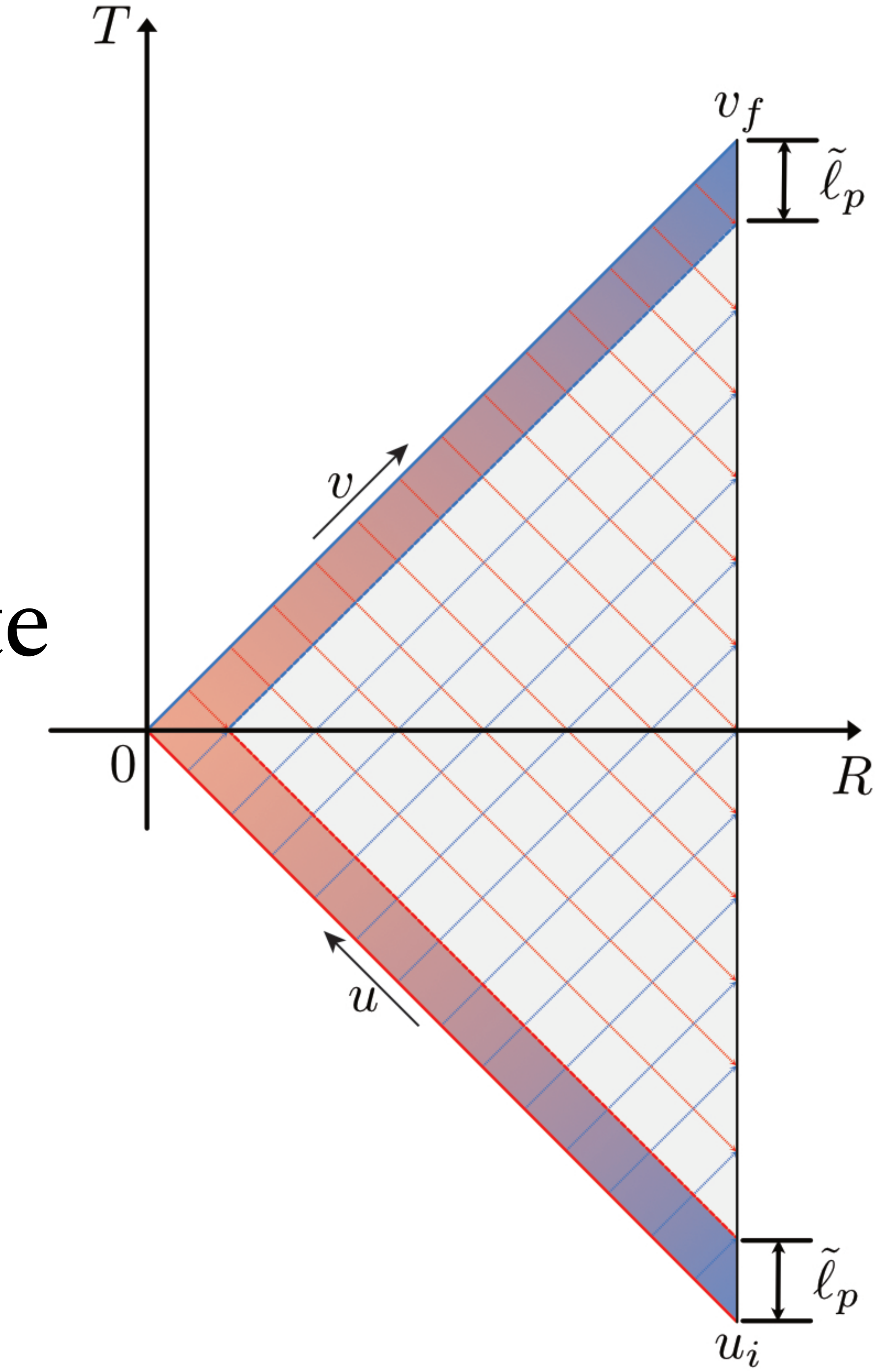
Coordinates Reduced by One

$$\left(\frac{d-2}{L^2} - \nabla_\perp^2\right)\left[h_{uu}(u,\mathbf{x}_\perp), h_{vv}(v,\mathbf{x}'_\perp)\right] = \frac{i}{2}\ell_p^{d-2}\delta(u-u_0)\delta(v-v_0)\delta^{d-2}(\mathbf{x}_\perp - \mathbf{x}'_\perp)$$

- What to do at the light front?
- Smear out horizon into stretched horizon of Planckian width
- Utilize Robertson uncertainty relation on min uncertainty state

$$\left\langle h_{uu}(u,\mathbf{x}_\perp)h_{uu}(u',\mathbf{x}'_\perp)\right\rangle = \frac{\ell_p^{d-2}}{2\pi\tilde{\ell}_p}\delta(u-u')f(\mathbf{x}_\perp;\mathbf{x}'_\perp)$$

$$\left\langle h_{vv}(v,\mathbf{x}_\perp)h_{vv}(v',\mathbf{x}'_\perp)\right\rangle = \frac{\ell_p^{d-2}}{2\pi\tilde{\ell}_p}\delta(v-v')f(\mathbf{x}_\perp;\mathbf{x}'_\perp)$$

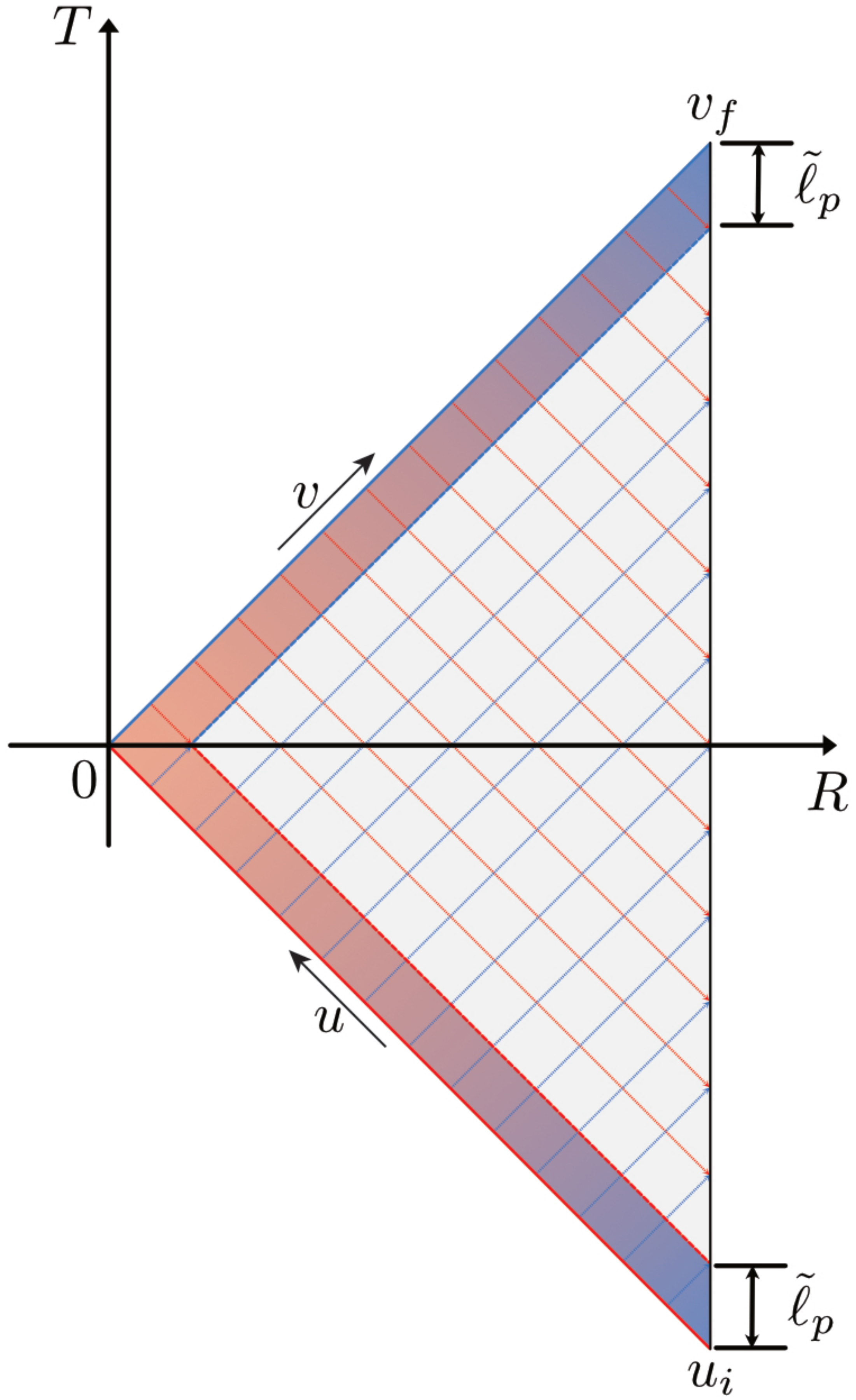


At a Light-Sheet Horizon

Integrated Quantum Uncertainty

$$\delta T^2_{\text{r.t.}} \sim \ell_p T_{\text{r.t.}}$$

d=4



$$\left\langle h_{uu}(u,\mathbf{x}_\perp)h_{uu}(u',\mathbf{x}'_\perp)\right\rangle = \frac{\ell_p^{d-2}}{2\pi\tilde{\ell}_p}\delta(u-u')f(\mathbf{x}_\perp;\mathbf{x}'_\perp)$$

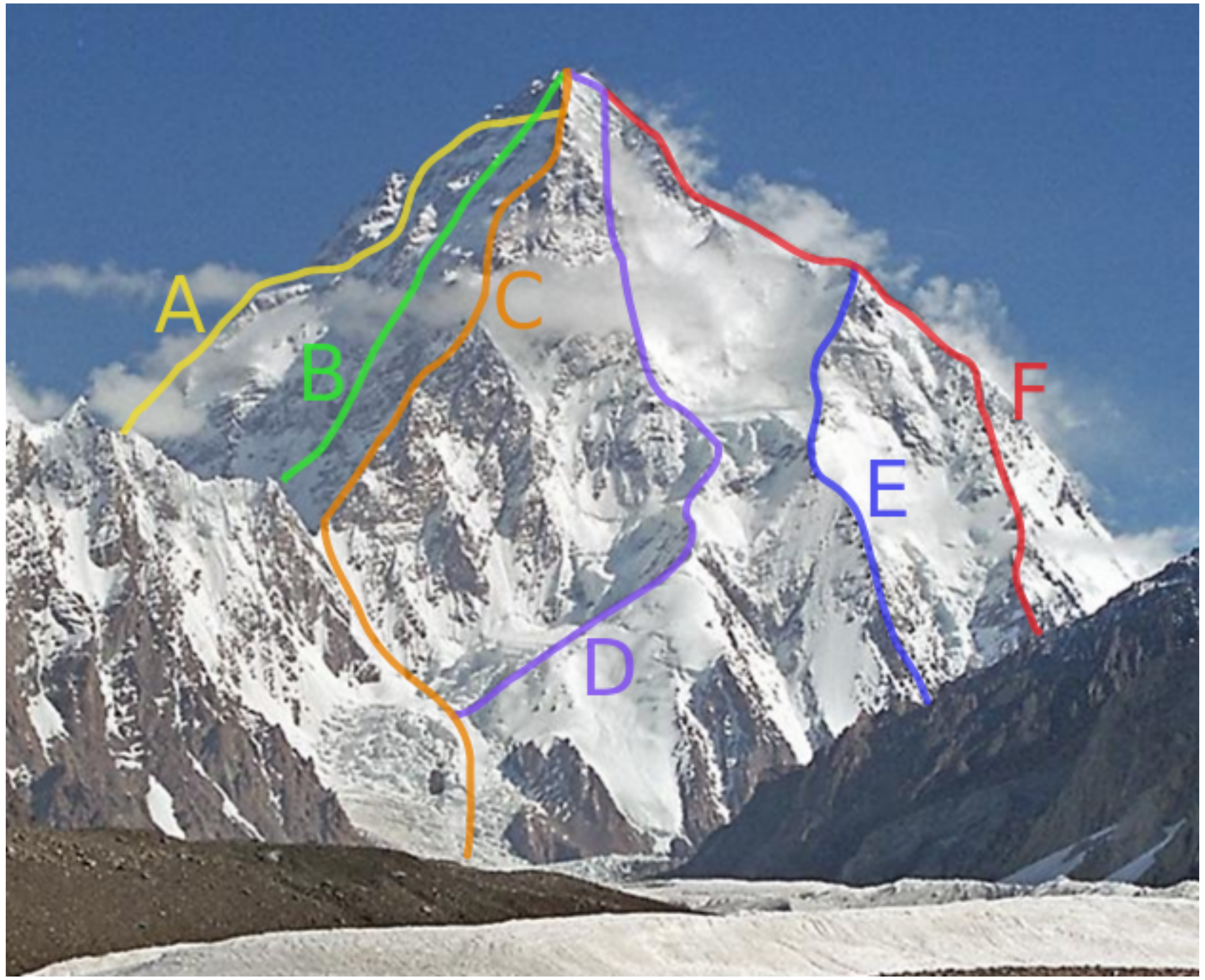
$$\left\langle h_{vv}(v,\mathbf{x}_\perp)h_{vv}(v',\mathbf{x}'_\perp)\right\rangle = \frac{\ell_p^{d-2}}{2\pi\tilde{\ell}_p}\delta(v-v')f(\mathbf{x}_\perp;\mathbf{x}'_\perp)$$

One Mountain, Many Faces

w/He,Sivaramakrishnan,Wilson

Equivalent physical descriptions

G. Gravitational Effective Action



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

w/Gukov, Lee 2205.02233

A. AdS/CFT

w/Verlinde 1911.02018

E. Hydrodynamics EFT

w/Zhang 2304.12349

H. "Pixellon"

KZ 2012.05870

w/Lee,Li,Chen 2209.07543

D. Shockwaves and Gravitational Memory

w/He, Raclariu 2305.14411

w/Verlinde, 2208.01059

B. Light Ray Operators

C. Gravitational effective action / saddle point expansion

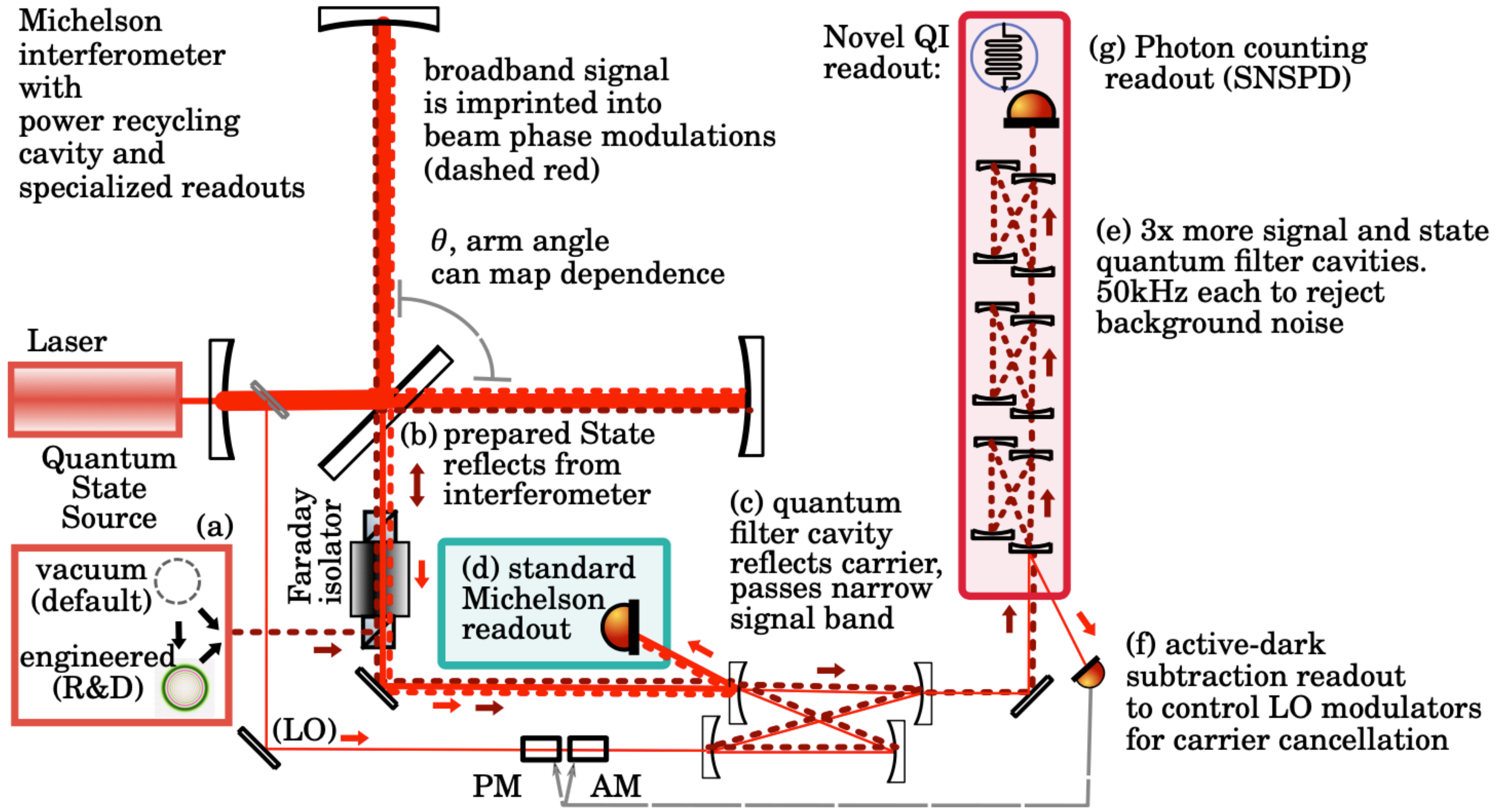
w/Banks, 2108.04806

Experiment GQuEST

Gravity from the Quantum Entanglement of SpaceTime

- Search for Fluctuations from Quantum Gravity

$$\frac{\delta L^2}{L^2} = \frac{l_p}{4\pi L}$$



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Quantum Gravity in the Infrared — UV in the IR

Concrete theoretical and experimental directions to determine observability of VZ effect

G. Gravitational Effective Action

w/ He, Sivaramakrishnan, Wilson

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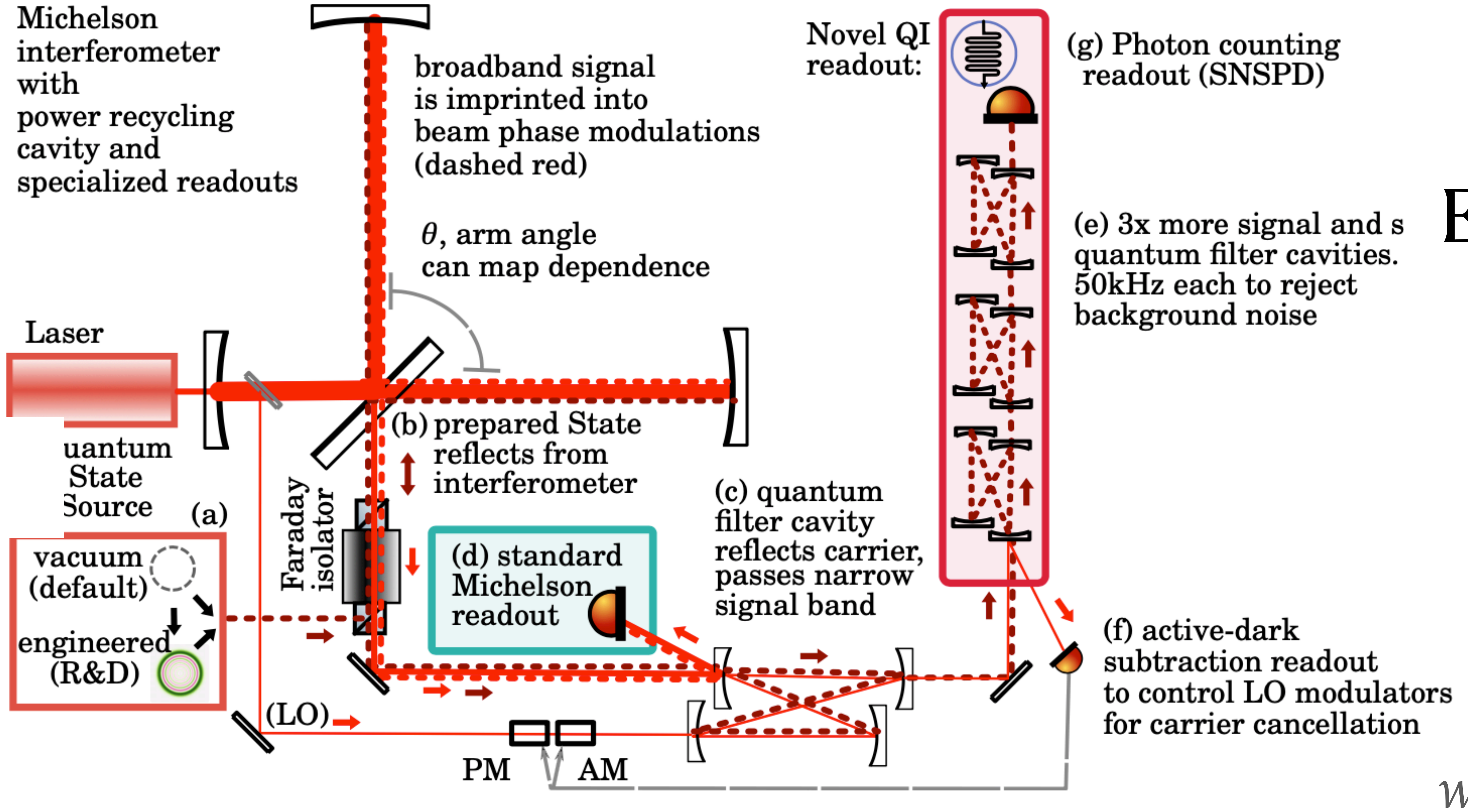

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