BURKE INSTITUTE

Caltech

# SIGNATURES OF QUANTUM GRAVITY IN THE INFRARED

*Summary: 2205.01799*
*Work with:*

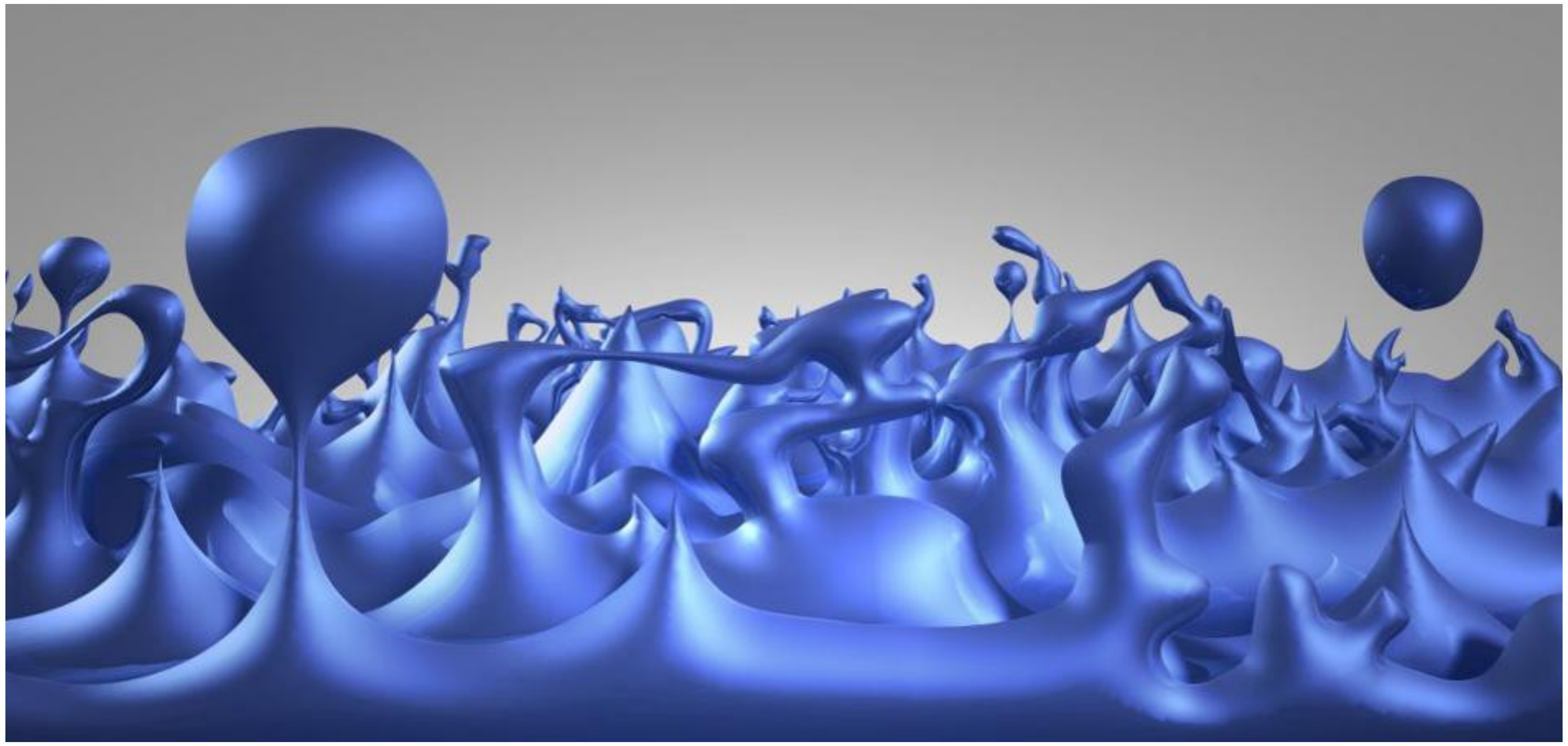
*Verlinde 1902.08207, 1911.02018, 2208.01059*
*KZ 2012.05870*
*Banks 2108.04806*
*Gukov, Lee, 2205.02233*
*Li, Lee, Chen 2209.07543*
*in progress w/ He, Sivaramakrishnan, Zhang, Lee*

*Kathryn Zurek*

# QUANTUM GRAVITY

—> FLUCTUATIONS IN SPACETIME

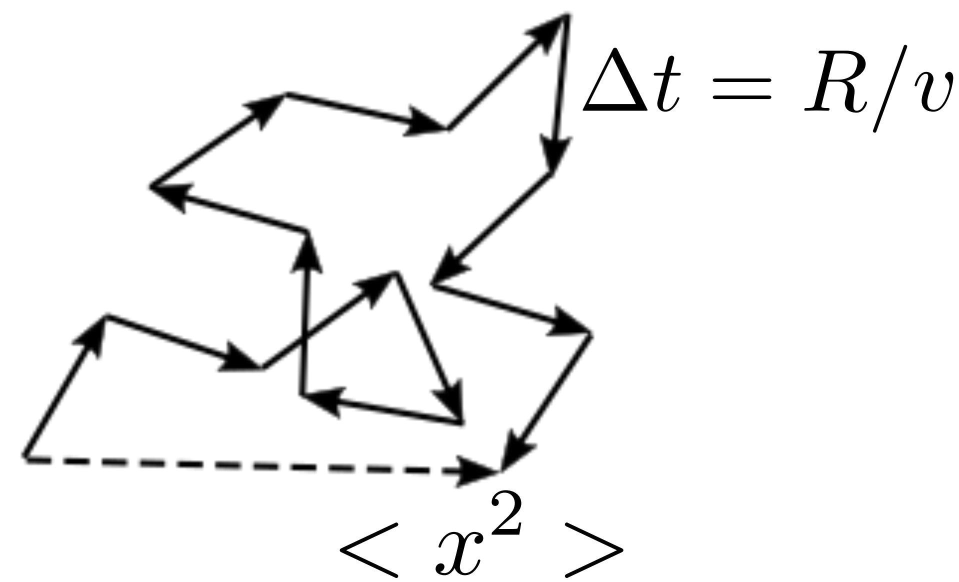
OLD VIEW: VISIBLE ONLY AT ULTRASHORT DISTANCES



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

# BROWNIAN NOISE

➤ UV Effects Can be Transmuted to the Infrared



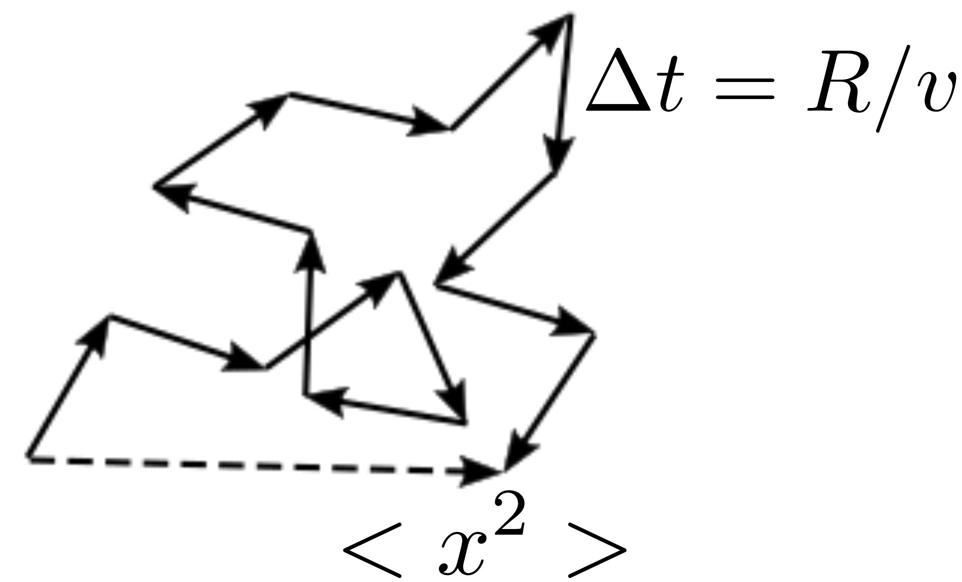

$$\langle x^2 \rangle = 2DT$$

$D \sim \Delta t$ *Observing time*

*UV Scale* *IR Scale*

# BROWNIAN NOISE

- UV Effects Can be Transmuted to the Infrared




$$\langle x^2 \rangle = 2DT \sim N \Delta t^2$$

*N = number of times a typical particle interacts*

$$N = \frac{T}{\Delta t} \qquad \Delta x \sim \sqrt{N} \Delta t$$

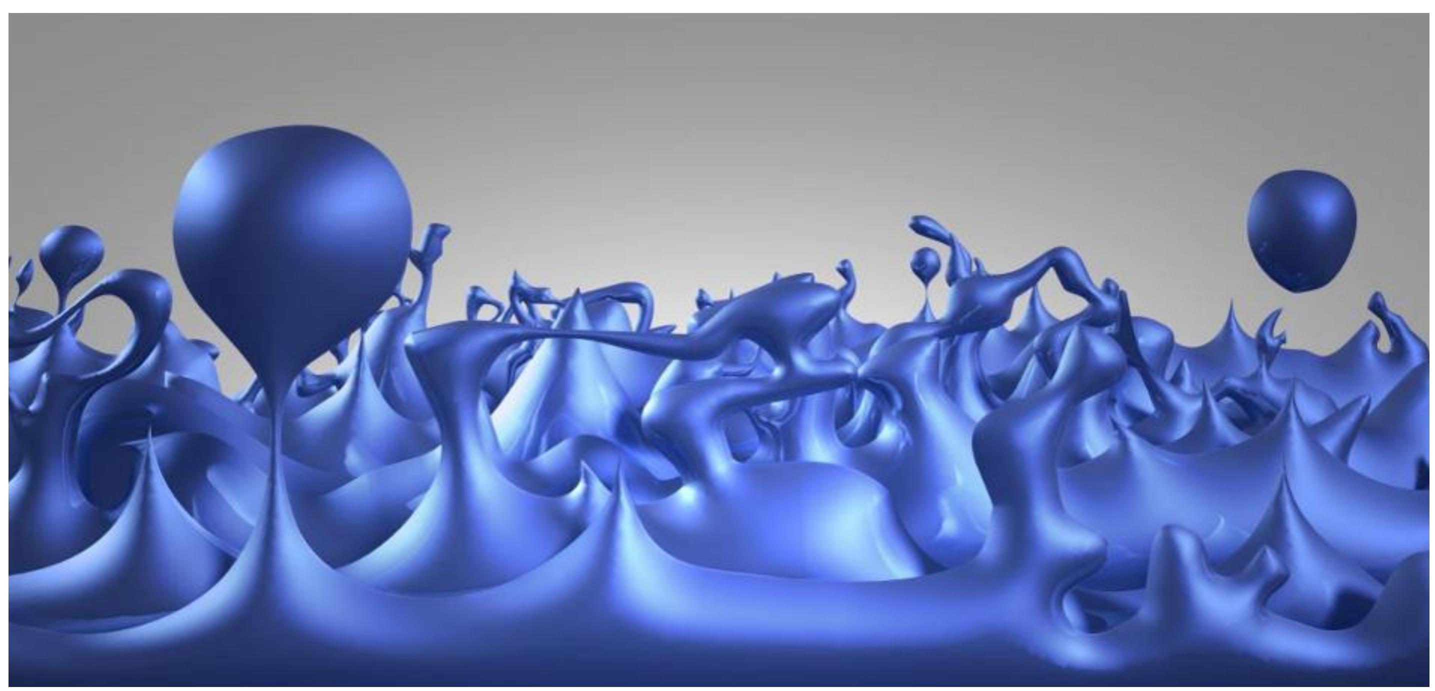
*Diffusion is simply "Random walk" or "Root N" statistics*

# QUANTUM GRAVITY

—> FLUCTUATIONS IN SPACETIME

NEW VIEW: NON-LOCALITY AND ENTANGLEMENT PLAY AN IMPORTANT ROLE IN QG

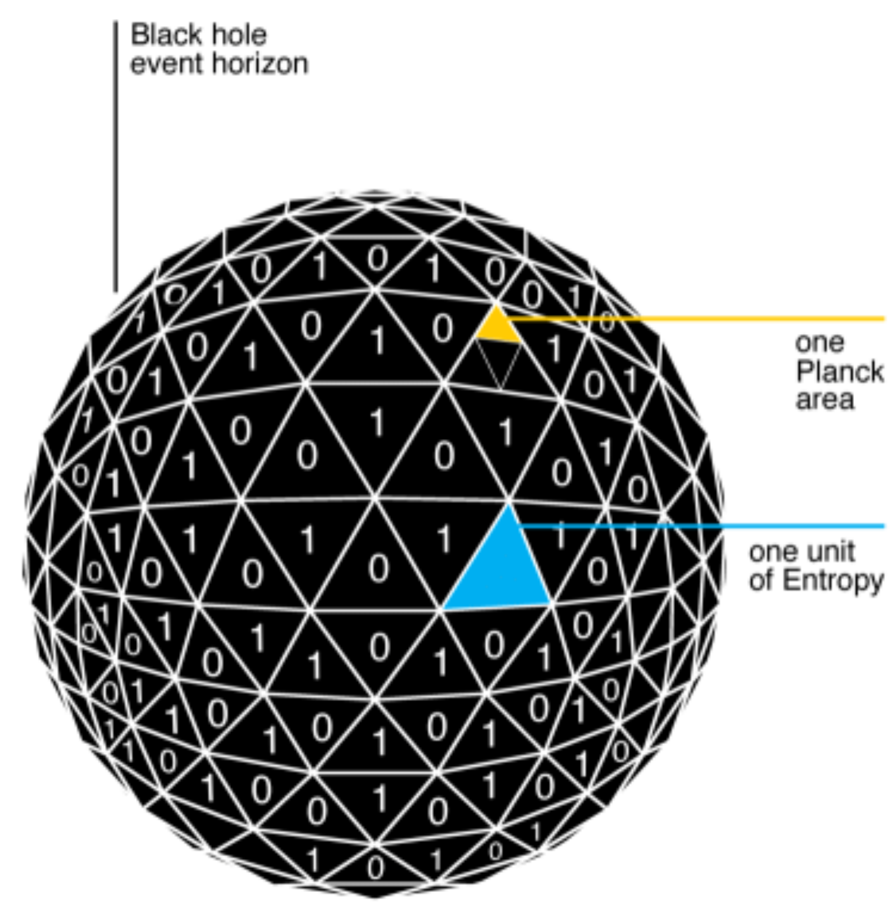
EXAMPLE: PHYSICS AT BLACK HOLE HORIZONS



# PHYSICS AT THE HORIZON

- Physics at horizons enters front and center into holography and QG
- Some naive EFT/ perturbative reasoning breaks down at the horizon
- UV / IR mixing seems important
- EFT vastly overcounts degrees-of-freedom of a spacetime volume bounded by surface of area A
- Entanglement between these degrees of freedom — inside and outside horizon — seems to be important

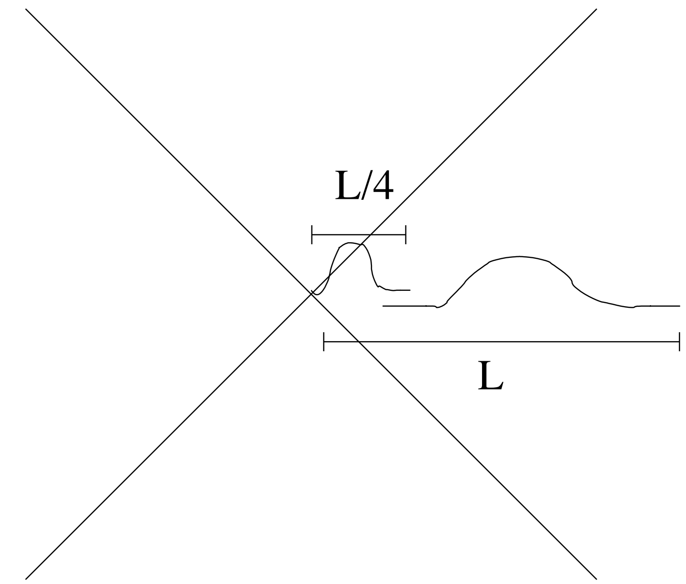
$$S = \frac{Area}{4\ell_p^2}$$



# THE QUANTUM WIDTH OF A (BH) HORIZON

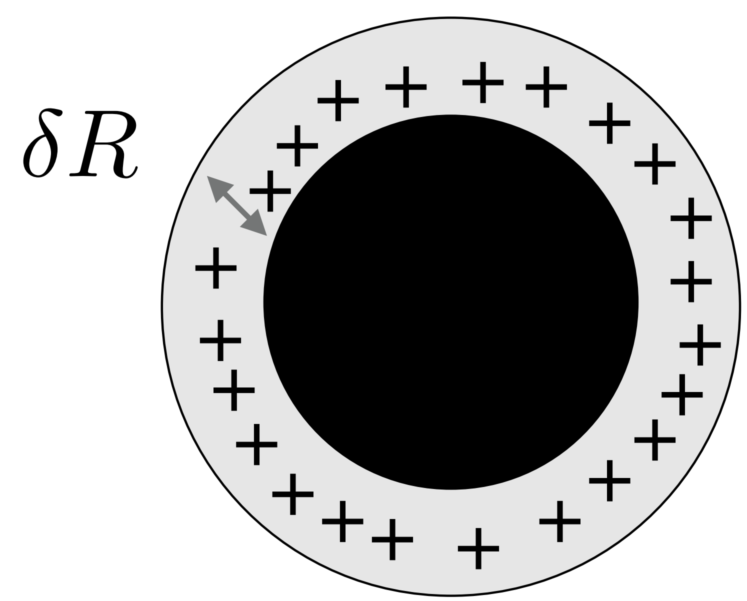
➤ Degrees-of-freedom ("pixels") can fluctuate

$$\delta R \underset{d=4}{\sim} \sqrt{l_p R}$$




*In any number of dimensions:*

$$\delta R^2 \sim \frac{R^2}{\sqrt{S_{\mathrm{BH}}}}$$

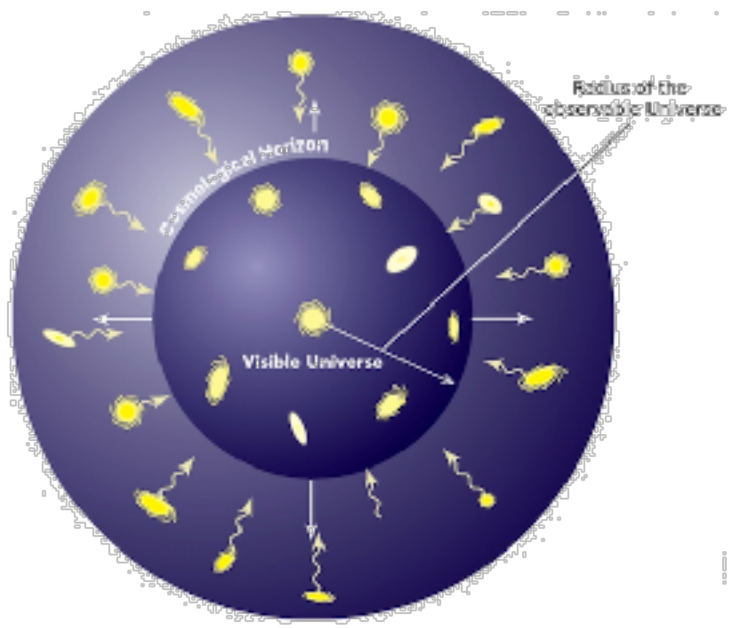



*Marolf 2003*

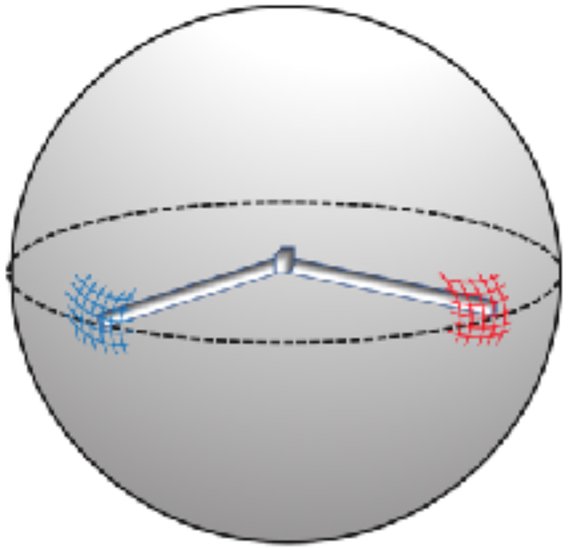
# HORIZONS

- An Experimental measurement defines a horizon

Black Hole Horizon




Cosmological Horizon

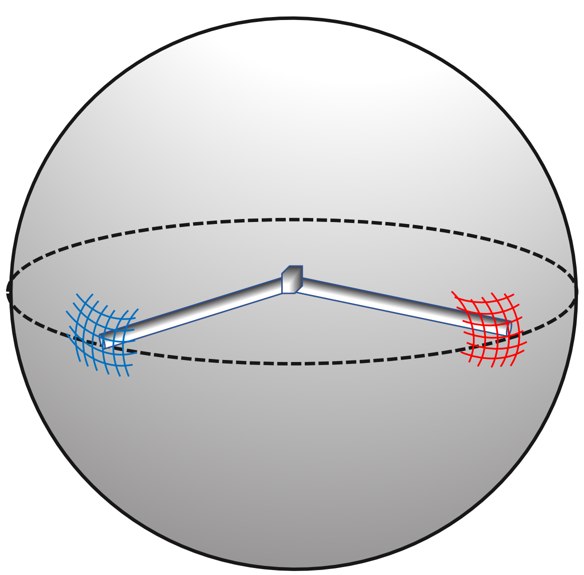


Flat Space Horizon

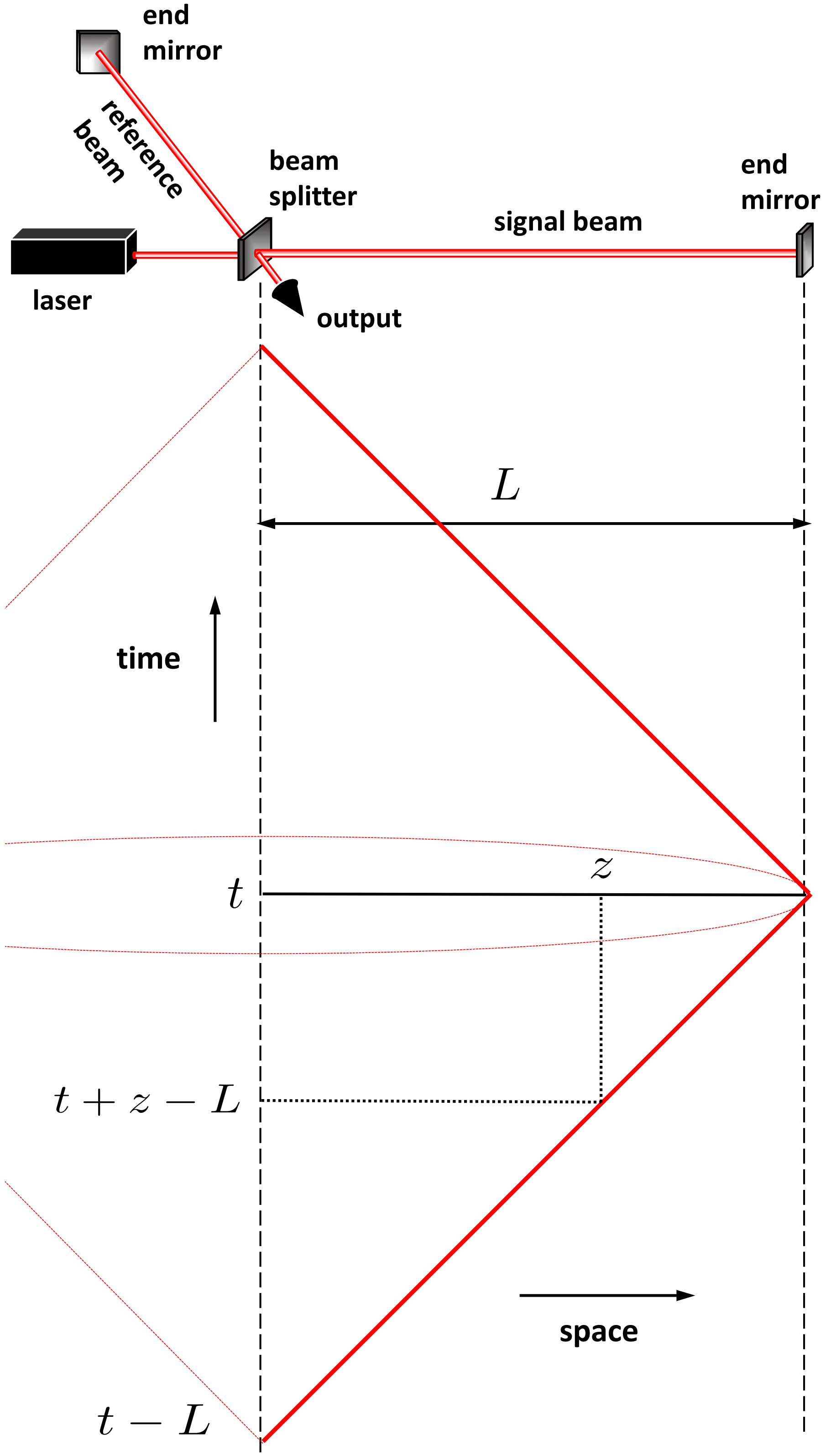
# HORIZONS AND EXPERIMENTS

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

- An experimental measurement defines a horizon
- Consider light beams of an interferometer



- *Traces out a causal diamond*

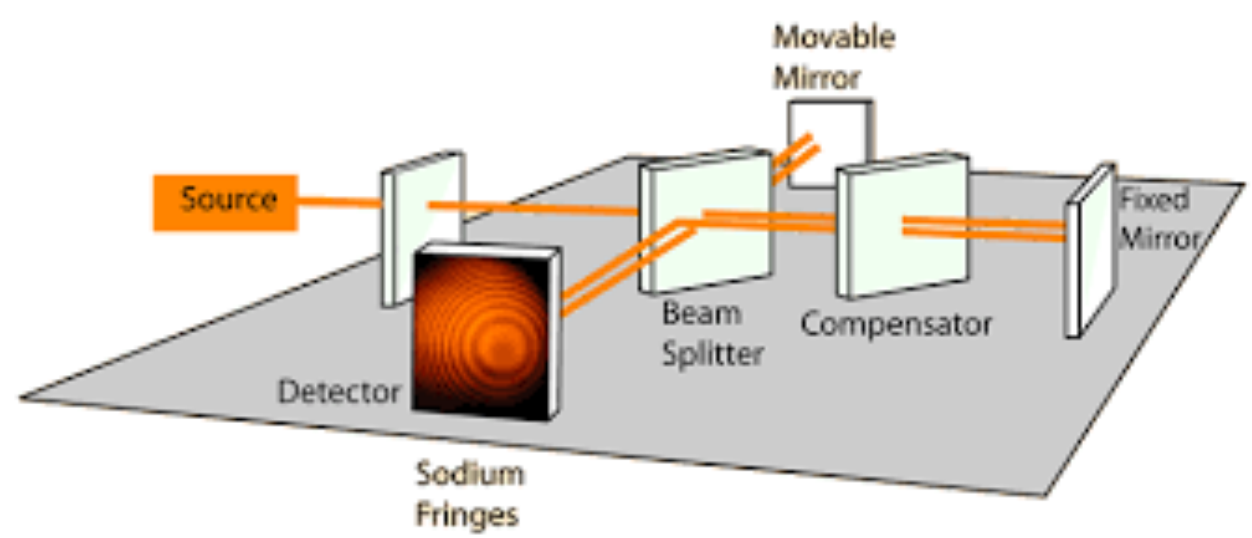


# WHAT LENGTH FLUCTUATION CAN BE MEASURED?

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

*Modern Interferometer Set-Up:*

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




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

*Parametrically the same as the black hole uncertainty*

# BLACK HOLE – (EMPTY!) CAUSAL DIAMOND DICTIONARY

| *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 $$M = \frac{1}{2\pi L}\Big(K - \langle K \rangle\Big) \qquad K = \int_B T_{\mu\nu}\zeta^\mu_K dB^\nu$$ |
| ➤ Thermodynamic free energy | ➤ Partition Function $$F = -\frac{1}{\beta}\log\,\mathrm{tr}\left(e^{-\beta K}\right)$$ |
| ➤ Entropy | ➤ Entanglement Entropy $$S = \langle K \rangle = \frac{A}{4G}$$ |

# PHYSICS AT HORIZONS — BH VS EMPTY SPACE

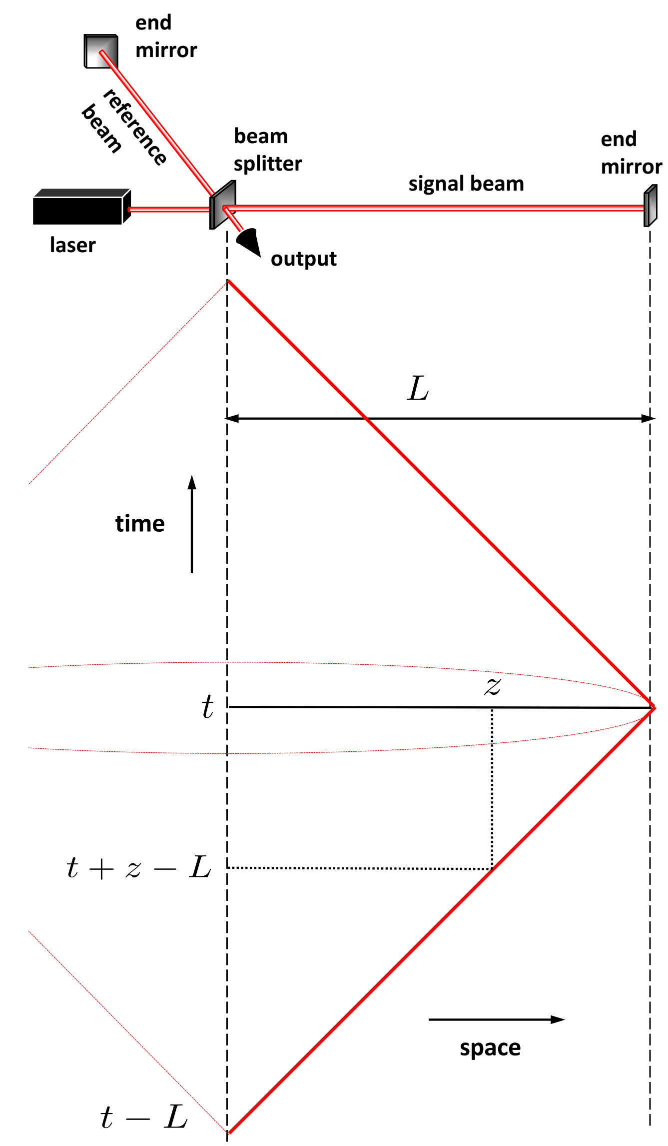
*E. Verlinde, KZ 1902.08207*
*E. Verlinde, KZ 1911.02018*

- 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”

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

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

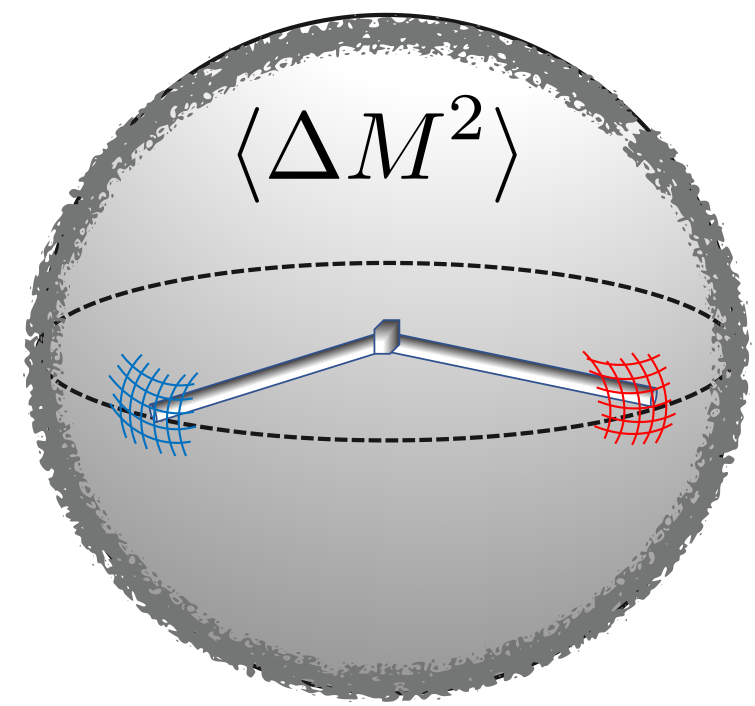
$$f(R) = 1 - \frac{R}{L} + 2\Phi$$



# OUR ARGUMENT (2 STEPS)

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

1. Calculate fluctuations in the energy of the vacuum
   A. In AdS/CFT this can be calculated with no assumptions.
   B. In Minkowski space, *we have made a case that the same relations hold*. *Banks, KZ 2108.04806*
      A. Interferometer on flat RS brane
      B. Dimensional reduction of flat E-H action to dilaton gravity a la Solodukhin
2. Calculate length fluctuation from vacuum energy fluctuation $\delta L \sim \sqrt{l_p L}$



# 1) CALCULATE VACUUM FLUCTUATION

- Number of holographic degrees of freedom is the entropy

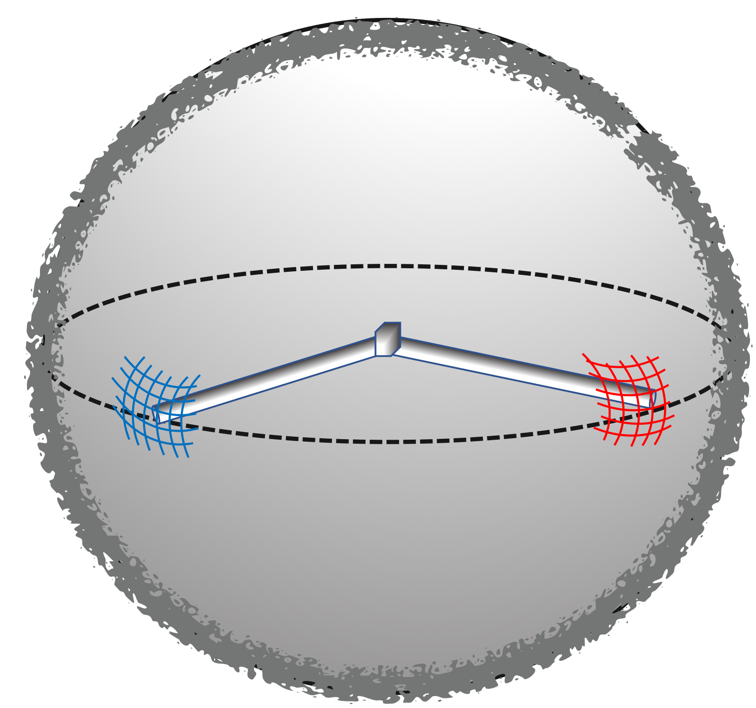
$$S = \frac{A}{4G_N} = \frac{8\pi^2 R^2}{l_p^2}$$

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

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

- Statistical argument:

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



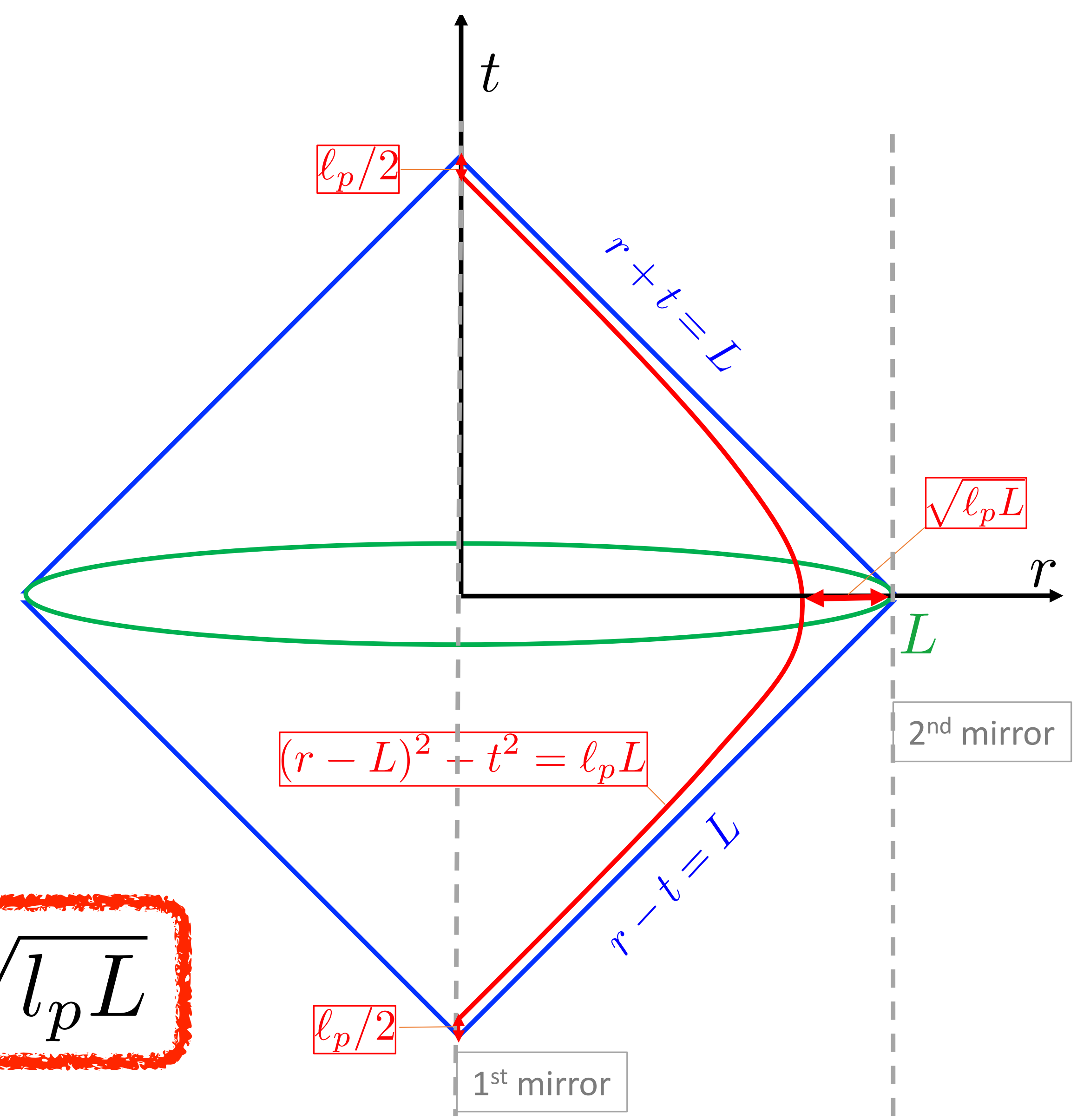
# 2) VACUUM FLUCTUATION SOURCES METRIC FLUCTUATION

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

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

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

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



# ONE MOUNTAIN, MANY FACES

G. Celestial CFT

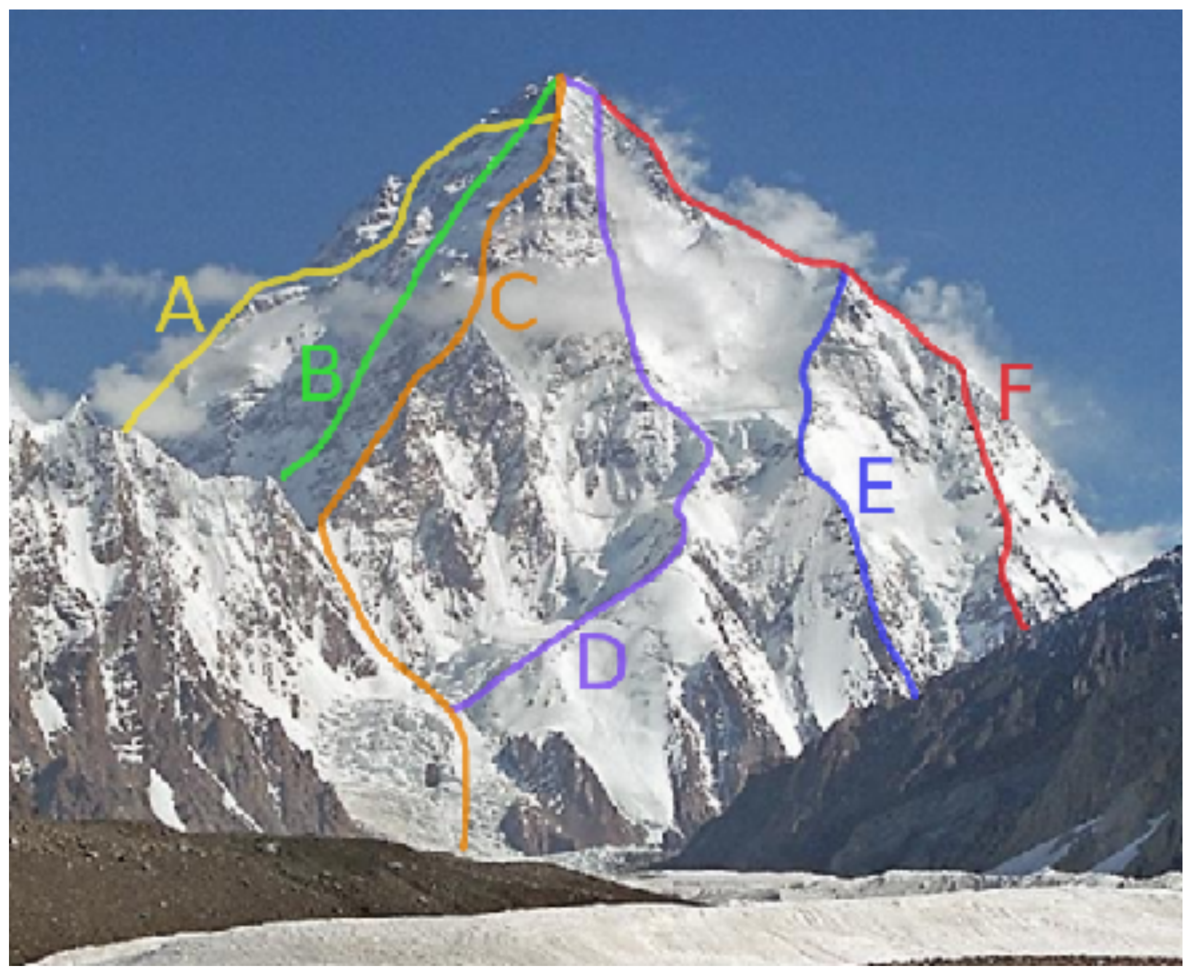
*w/ He, Raclariu in progress*

F. 2-d Models, e.g. JT gravity *w/Gukov, Lee 2205.02233*

H. Effective Model— pixellon

*Zurek 2012.05870*

*w/Li, Lee, Chen 2209.07543*




A. AdS/CFT

*w/Verlinde 1911.02018*

E. Hydrodynamics EFT

*w/Zhang in progress*

B. Light Ray Operators / Shockwaves

*w/Verlinde, 2208.01059*

D. 4-pt correlators

*w/ He, Sivaramakrishnan in progress*

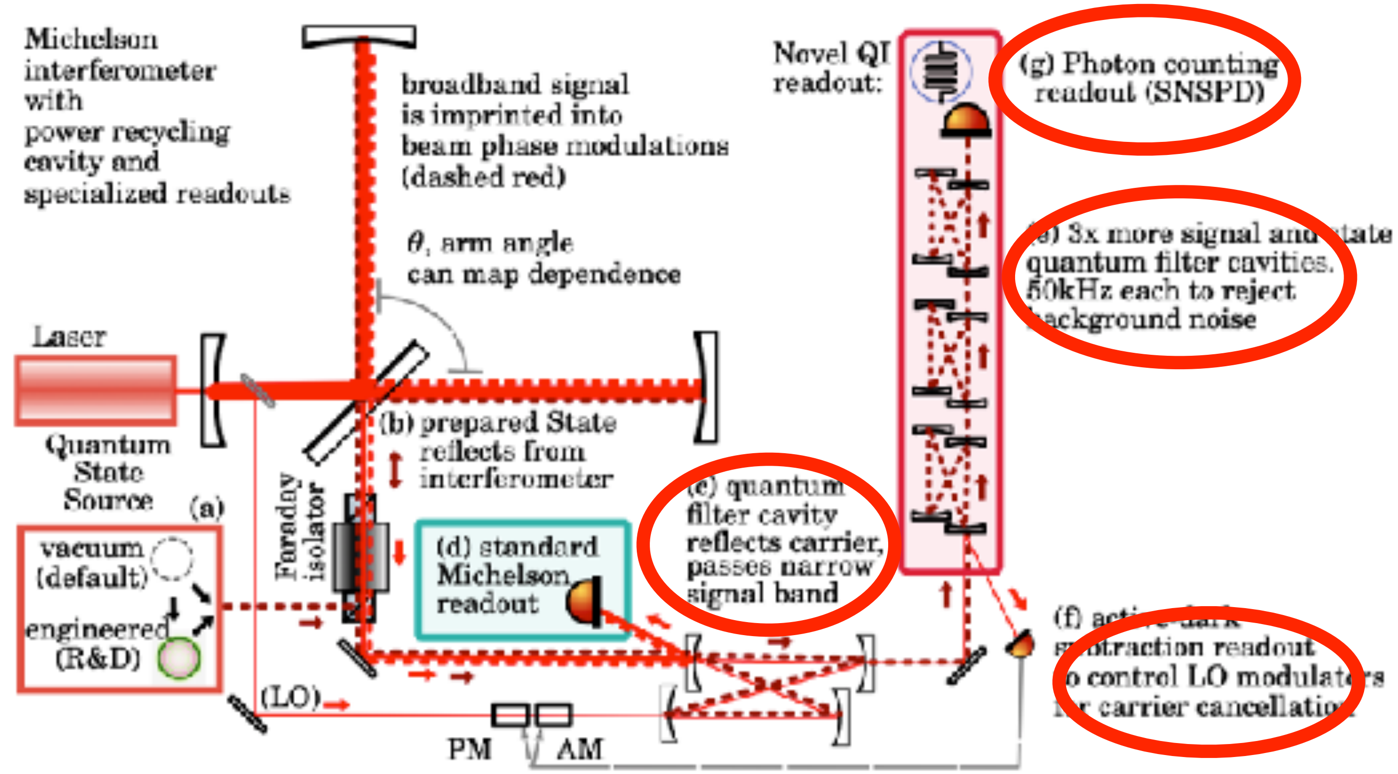
C. Gravitational effective action / saddle point expansion

*w/Banks, 2108.04806*

# EXPERIMENTAL MEASUREMENT OF THEORETICALLY ESTIMATED EFFECT

- Gravity from the Quantum Entanglement of SpaceTime

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

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HEISING-SIMONS FOUNDATION

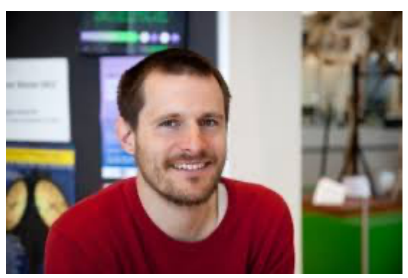
# THE QURIOS COLLABORATION

Parikh, particle theory / gravity, ASU

Verlinde, string theory / emergent gravity, UvA

Zurek, particle theory / Effective field theory & QG, Caltech

Giddings, quantum gravity / black holes, UCSB



Freivogel, string theory / cosmology & early universe, UvA

Chen, astrophysics / gravitational waves & precision measurement, Caltech

Keeler, string theory / fluid-gravity, ASU

ASU

Caltech

UNIVERSITY OF AMSTERDAM

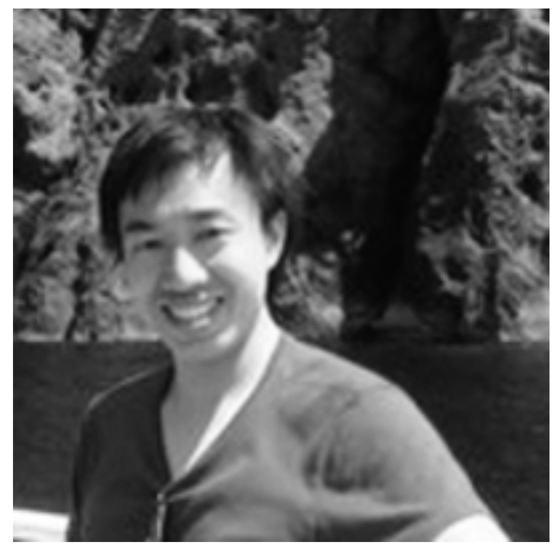
UCSB

HEISING-SIMONS FOUNDATION

# THE QURIOS COLLABORATION

➤ Inaugural Heising-Simons Fellows

*Lars Aalsma*



*Temple He*

*Ana-Maria Raclariu*

*Claire Zukowski*

*Allic Sivaramakrishnan*

*Kwinten Fransen*

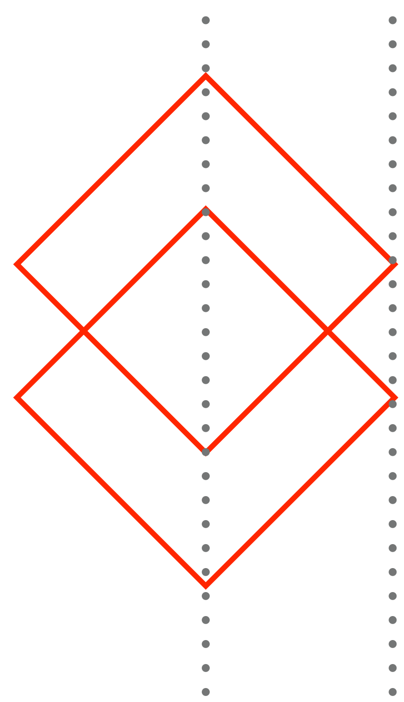
*Dominik Neuenfeld*

# MOTIVATION: EXPERIMENTAL MEASUREMENT OF THEORETICALLY ESTIMATED EFFECT

- Theory is generically predictive: amplitude (and angular correlations, assuming symmetric geometry)
- Theory is not yet powerful enough to give power spectral density

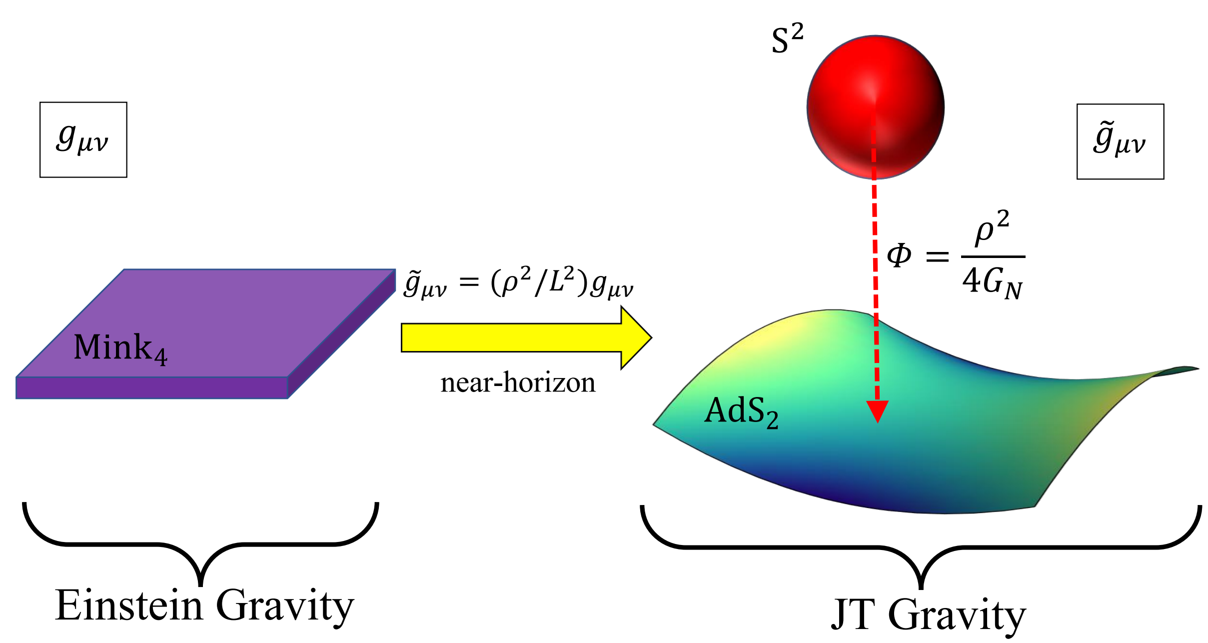
$$S(\omega, t) = \int_{-\infty}^{\infty} d\tau \left\langle \frac{\delta L(t)}{L} \frac{\delta L(t-\tau)}{L} \right\rangle e^{-i\omega\tau}$$

  - which corresponds to being able to correlate two causal diamonds



# MOTIVATION: ASSUMING POWER IN LOW-ELL MODES

- e.g. w/ Gukov, Lee: in near horizon limit, 4-d Einstein-Hilbert action dimensionally reduces to Jackiw-Teitelboim gravity in 2-d on class of spherically symmetric metrics



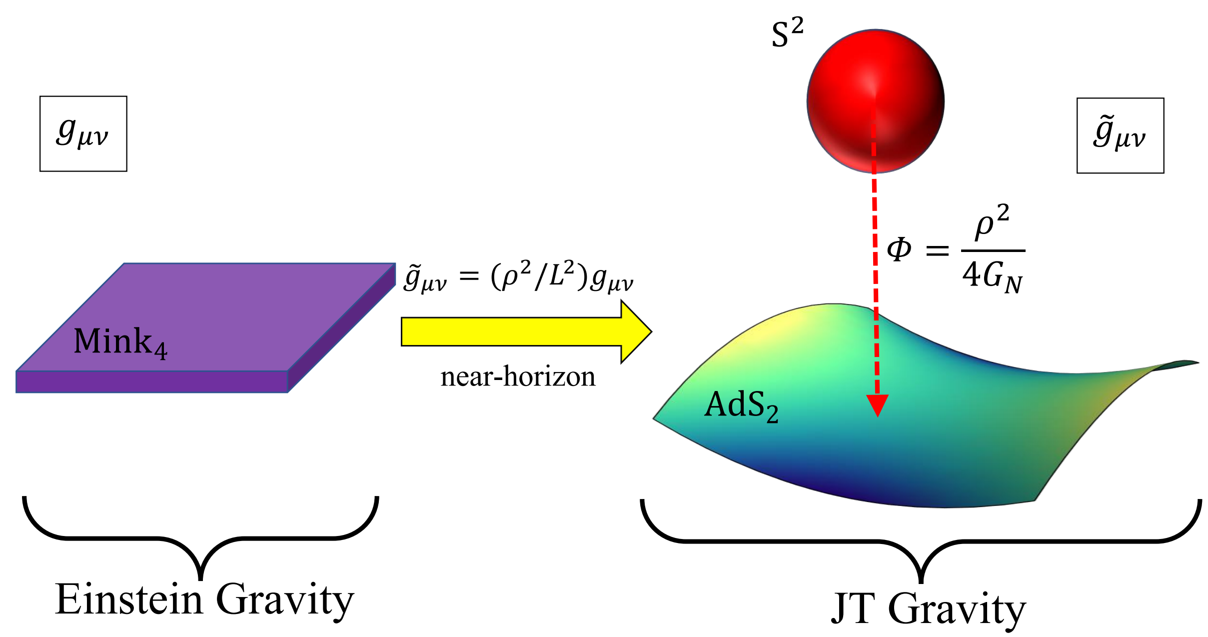

$$ds^2 = \frac{\rho^2}{L^2}\left(\frac{L^2}{\rho^2} g_{ab} dx^a dx^b + L^2 d\Omega_2^2\right)$$

$$I_{\mathrm{EH}} = \frac{1}{16\pi G_N}\int_{M_4} d^4x \sqrt{-g_4} R_4$$

$$I_{\mathrm{GHY}} = \frac{1}{8\pi G_N}\int_{\partial M_4} d^3x \sqrt{-\gamma_3} K_3$$

# MOTIVATION: ASSUMING POWER IN LOW-ELL MODES

- e.g. w/ Gukov, Lee: in near horizon limit, 4-d Einstein-Hilbert action dimensionally reduces to Jackiw-Teitelboim gravity in 2-d on class of spherically symmetric metrics

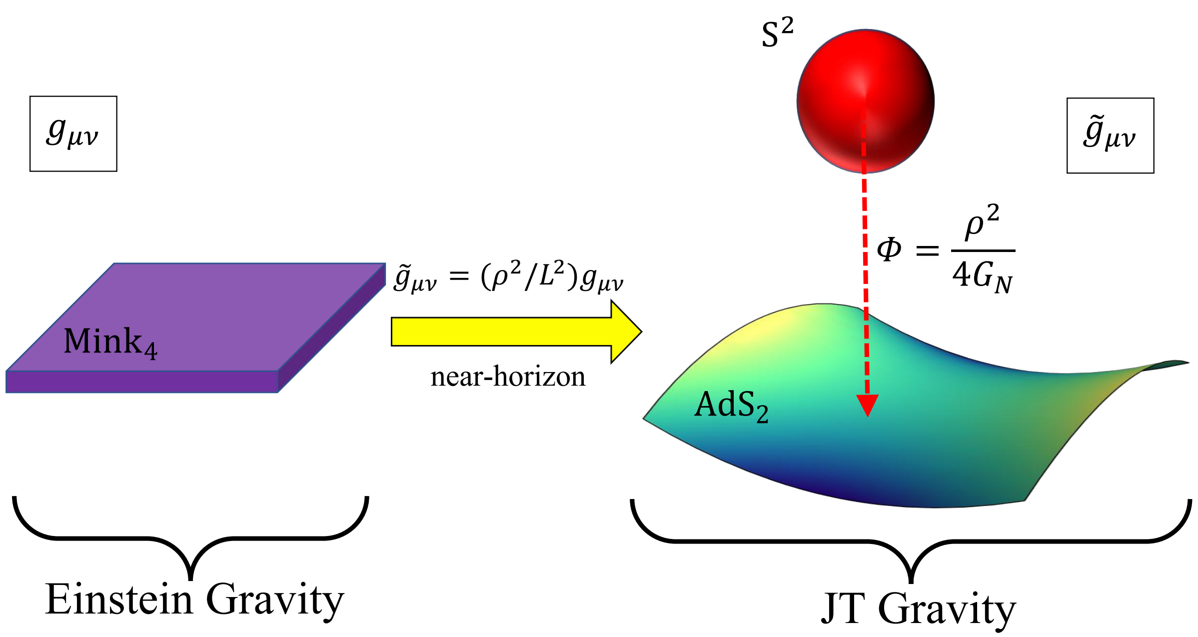



*in near-horizon limit*

$$I = \frac{1}{4G_N}\int_{\tilde{M}_2} d^2x\sqrt{-\tilde{g}_2}\left(\rho^2\tilde{R}_2 + \cancel{6(\tilde{\nabla}\rho)^2} + \frac{2}{L^2}\rho^2\right) + \frac{1}{2G_N}\int_{\partial\tilde{M}_2} dx^0\sqrt{-\tilde{\gamma}_1}\rho^2\tilde{K}_1$$

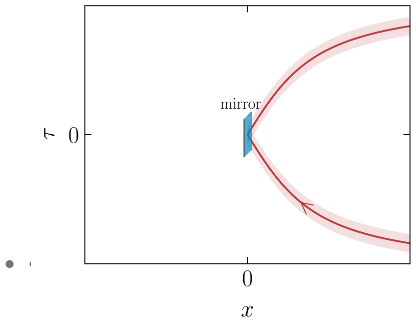
# MOTIVATION: ASSUMING POWER IN LOW-ELL MODES

- e.g. w/ Gukov, Lee: in near horizon limit, 4-d Einstein-Hilbert action dimensionally reduces to Jackiw-Teitelboim gravity in 2-d on class of spherically symmetric metrics

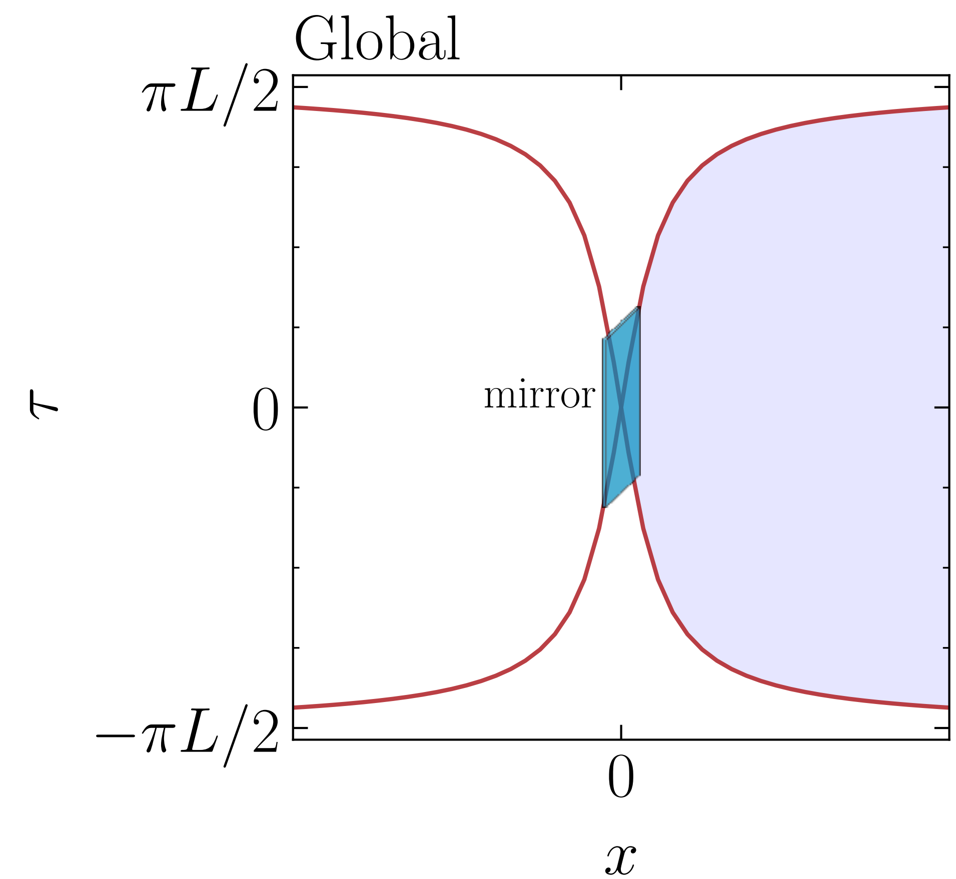



$$I = \int_{\tilde{M}_2} d^2x\sqrt{-\tilde{g}_2}\Phi\left(\tilde{R}_2 + \frac{2}{L^2}\right) + 2\int_{\partial\tilde{M}_2} dx^0\sqrt{-\tilde{\gamma}_1}\Phi\tilde{K}_1$$

# MOTIVATION: JT SOLUTION




- JT gravity reduces to 1-d QM problem that can be solved exactly
- Two-sided geometry allows us to track one clock w.r.t. other




$$\Omega = d\delta \wedge dH = dL_g \wedge dP$$

*Harlow and Jafferis 1804.01081*

$$-I_E = \text{constant} - \frac{S}{16L^2}(L_g - L_{g,\text{peak}})^2$$

$$\Delta T^2_{\text{r.t.}} = \frac{l_p L}{\pi}$$

*Gukov, Lee, KZ 2205.02233*

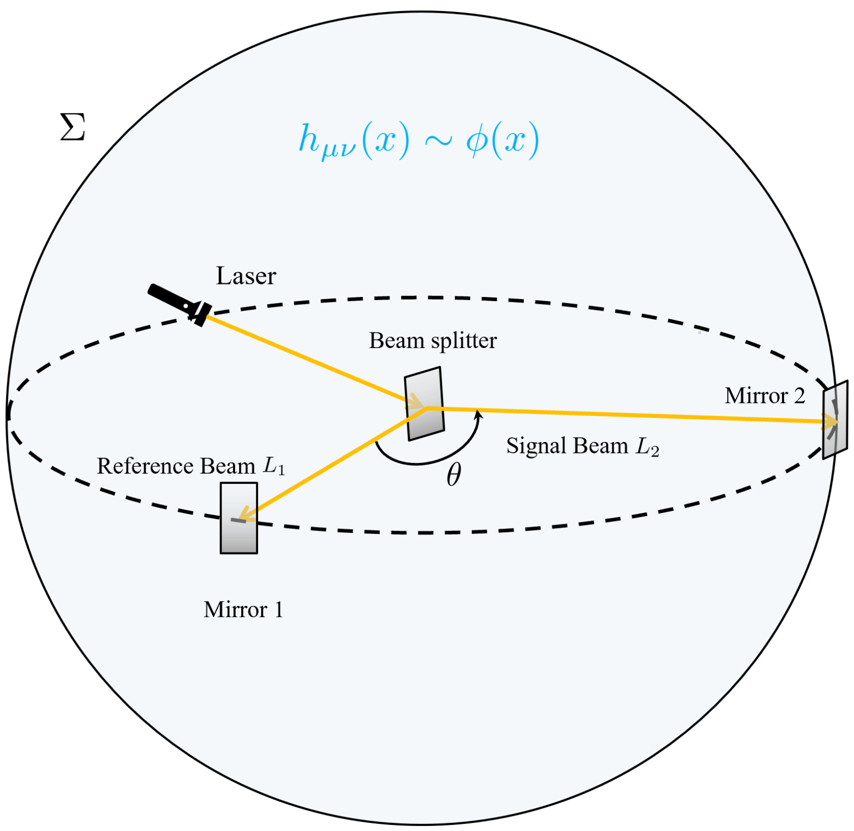
# EQUIVALENT PHYSICAL DESCRIPTIONS

- The formalism will become powerful enough to calculate everything for experiment from first principles
- We already have several handles that will help us compute all information, but these calculations are not complete
  - Wilson loop / worldlines
  - Hydrodynamic effective theory / Goldstone modes
  - Multi-soft emission?

# EQUIVALENT PHYSICAL DESCRIPTIONS — A MODEL FOR PHENO

*KZ 2012.05870*

- The "pixellon."
- Bosonic excitation modeling hydro mode




$$ds^2 = -dt^2 + (1-\phi)(dr^2 + r^2 d\Omega^2)$$

$$\mathrm{Tr}\left(\rho_{\text{pix}} a^\dagger_{\mathbf{p}_1} a_{\mathbf{p}_2}\right) = (2\pi)^3 \sigma_{\text{pix}}(\mathbf{p}_1)\delta^{(3)}(\mathbf{p}_1 - \mathbf{p}_2)$$

*Number of bits or "pixels"*

$$S_{\text{ent}} = \mathcal{N} = \frac{A}{4G}$$

*Li, Lee, Chen, KZ 2209.07543*

# PIXELLON FROM MODULAR FLUCTUATIONS

- What is the density of states?
- Pixellon is a scalar field (hydro) with thermal distribution

$$\sigma_{\text{pix}}(\mathbf{p}) = \frac{1}{e^{\beta\omega(\mathbf{p})} - 1} \approx \frac{1}{\beta\omega(\mathbf{p})}$$

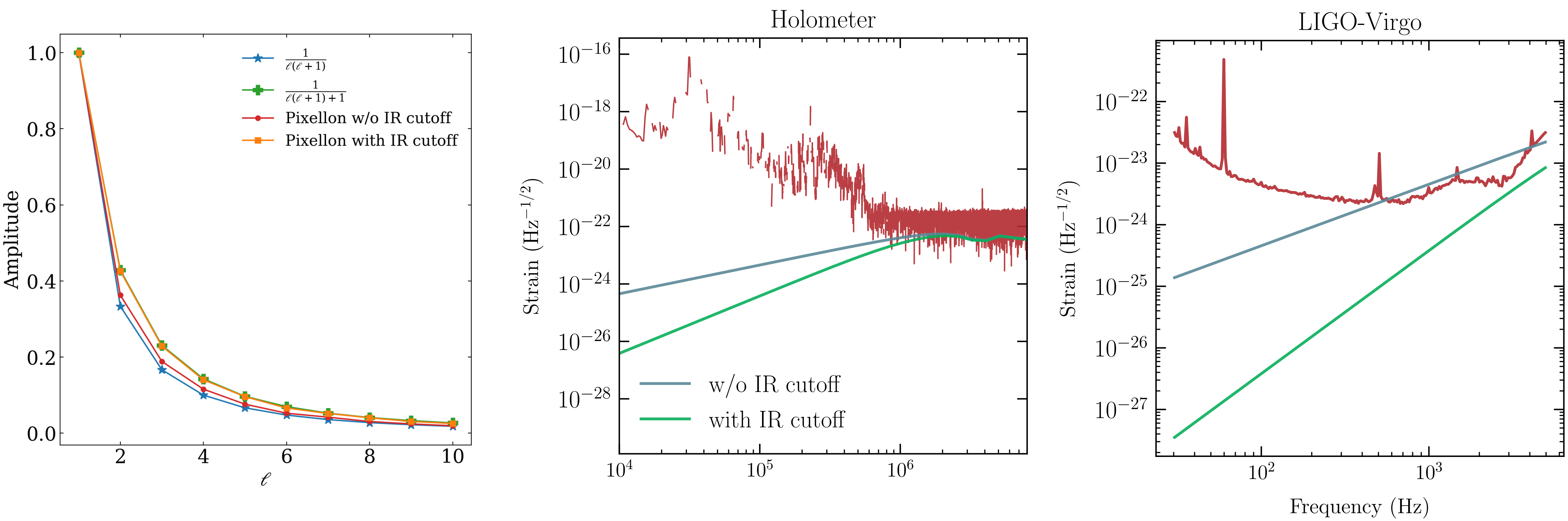
- The pixellon characterizes vacuum fluctuations, so the energy per d.o.f. should be given by the modular fluctuation

$$\beta\omega(\mathbf{p}) \sim \frac{\beta|\Delta K|}{S_{\text{ent}}} = \frac{1}{\sqrt{S_{\text{ent}}}}$$

$$\sigma_{\text{pix}}(\mathbf{p}) = \frac{a}{l_p\omega(\mathbf{p})}$$

# EQUIVALENT PHYSICAL DESCRIPTIONS — A MODEL FOR PHENO

- Distinctive Angular Correlations Predicted already in VZ1




- Consistent with LIGO and Holometer data

*Li, Lee, Chen, KZ 2209.07543*

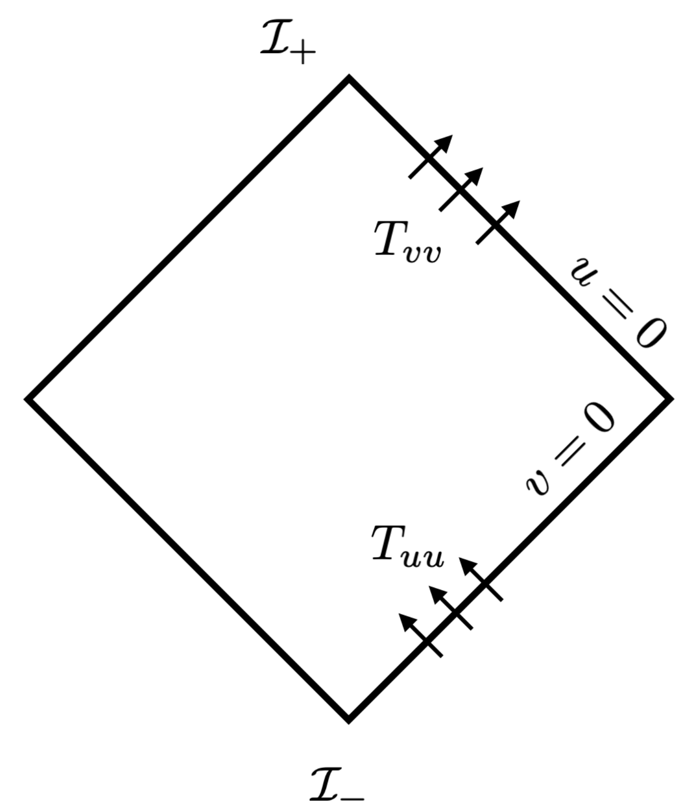
# WHAT ARE WE TESTING?

- Fundamental uncertainty in light ray operators…

$$X^u(u,\Omega) = L - u + \delta u(u,\Omega)$$

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

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




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

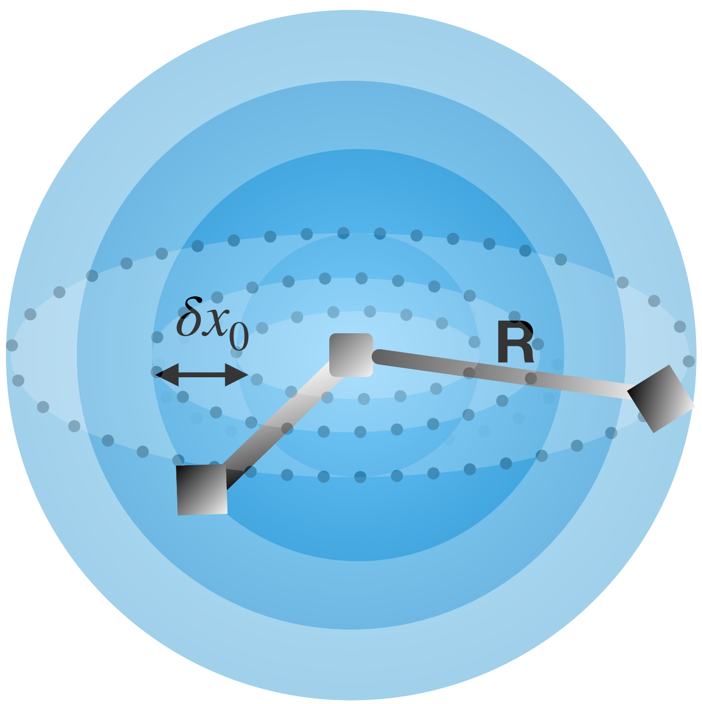
$$I_{on-shell} = \int d^{d-2}y \left[\int_{-\infty}^{0} du\, X^u T_{uu} + \int_0^{\infty} dv\, X^v T_{vv}\right] \equiv K$$

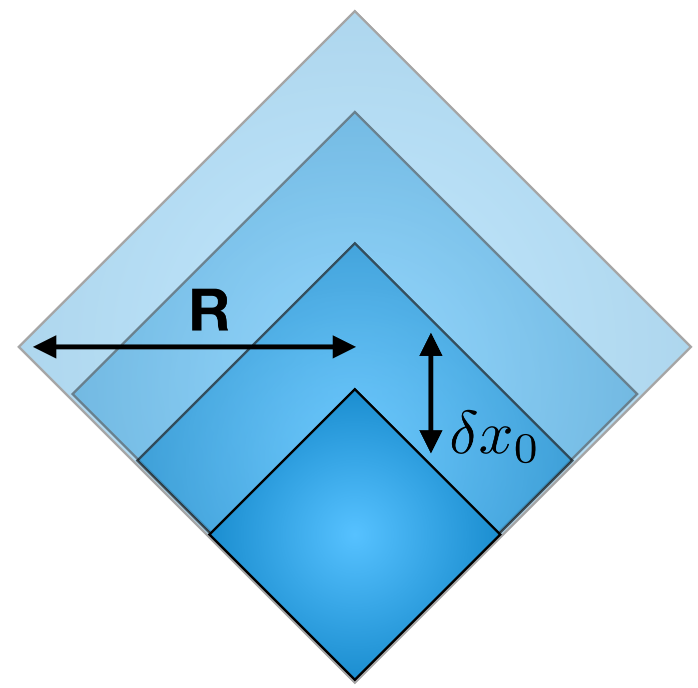
$$\langle K\rangle = \langle(\Delta K)^2\rangle = \frac{A_\Sigma}{4G}$$

*Verlinde, KZ 2208.01059*

# WHAT ARE WE TESTING?

- And their Accumulation into Infrared




$$\delta R^2 \simeq \delta x_0^2\, \mathcal{N} = \frac{R^2}{d-2}\frac{1}{\sqrt{S_0}}$$

# QUANTUM GRAVITY IN THE INFRARED — UV IN THE IR

*Concrete theoretical and experimental directions to determine observability of VZ effect*

G. Celestial CFT

*w/ He, Raclariu in progress*

F. 2-d Models, e.g. JT gravity *w/Gukov, Lee 2205.02233*

H. Effective Model— pixellon

*Zurek 2012.05870*

*w/Li, Lee, Chen 2209.07543*

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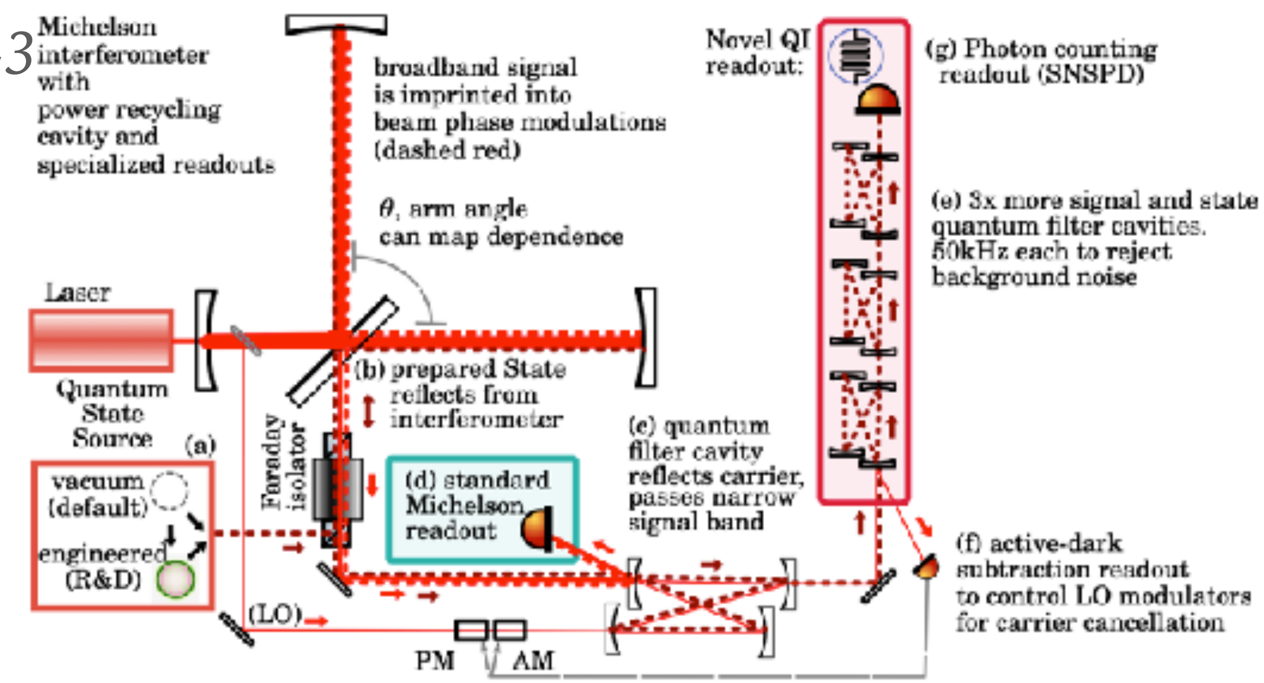
*w/Verlinde 1911.02018*

B. Light Ray Operators / Shockwaves

*w/Verlinde, 2208.01059*




E. Hydrodynamics EFT

*w/Zhang in progress*

D. 4-pt correlators / TOCs/OTOCs

*w/ He, Sivaramakrishnan in progress*

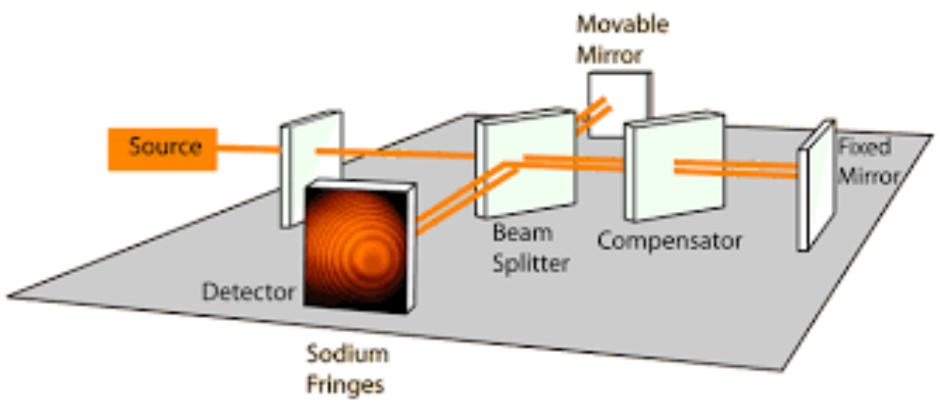
C. Gravitational effective action / saddle point expansion

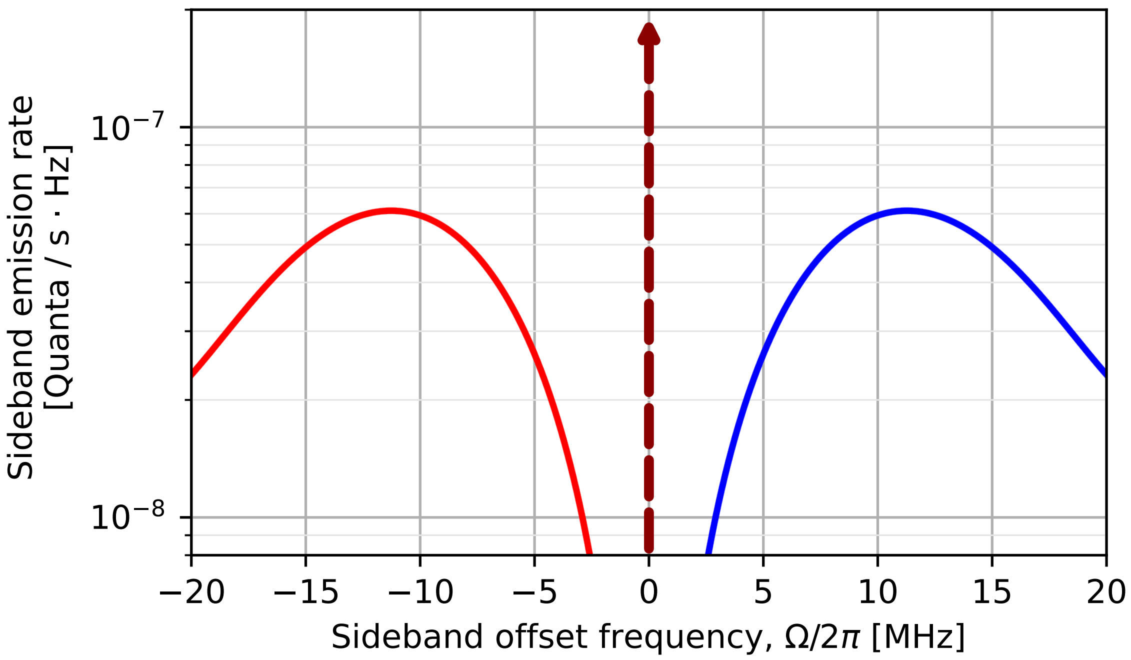
*w/Banks, 2108.04806*

# EXPERIMENTAL MEASUREMENT OF THEORETICALLY ESTIMATED EFFECT

➤ Time dependence of the effect will determine the signatures

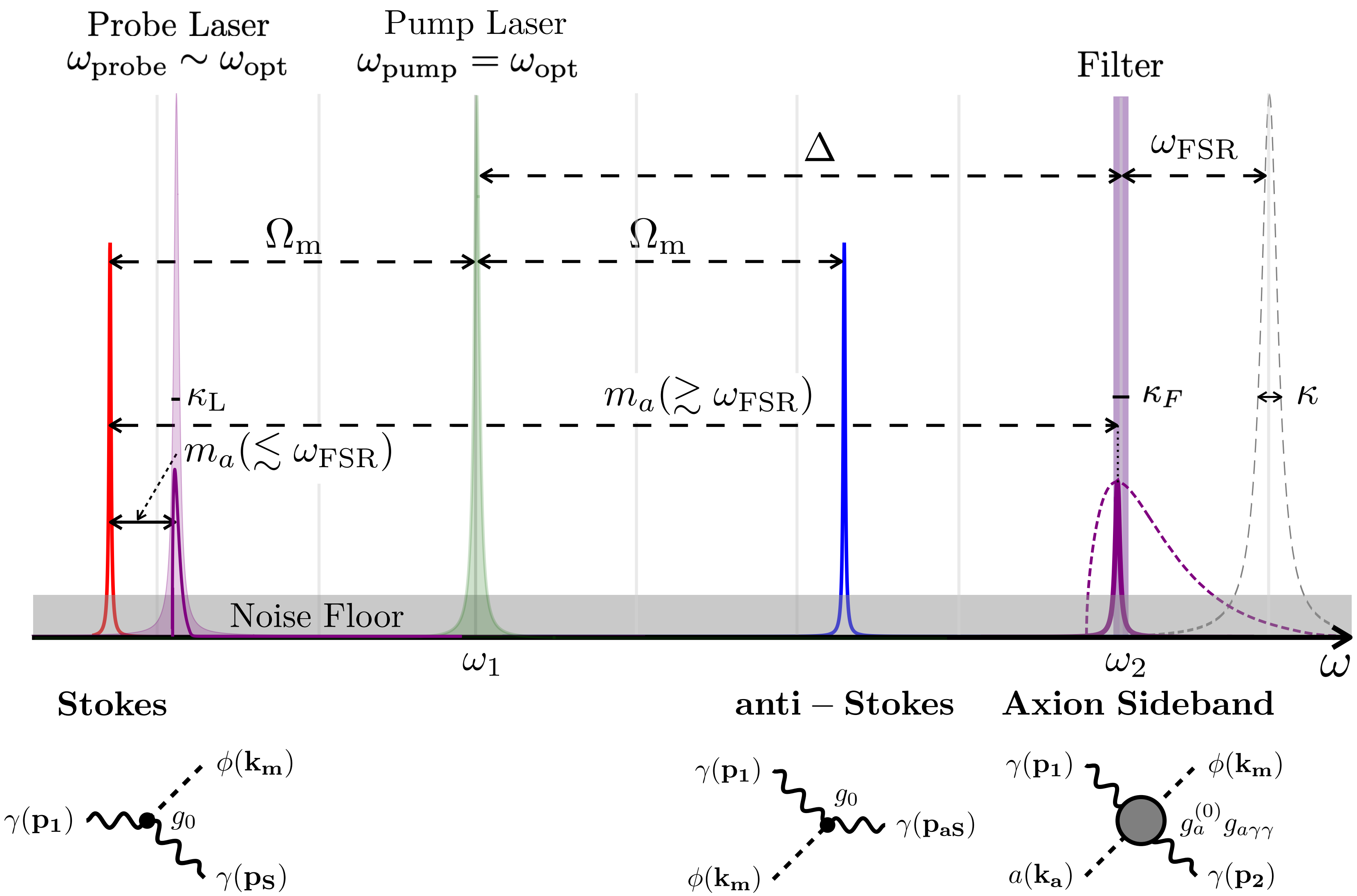
*L. Mcculler, 2211.04016*

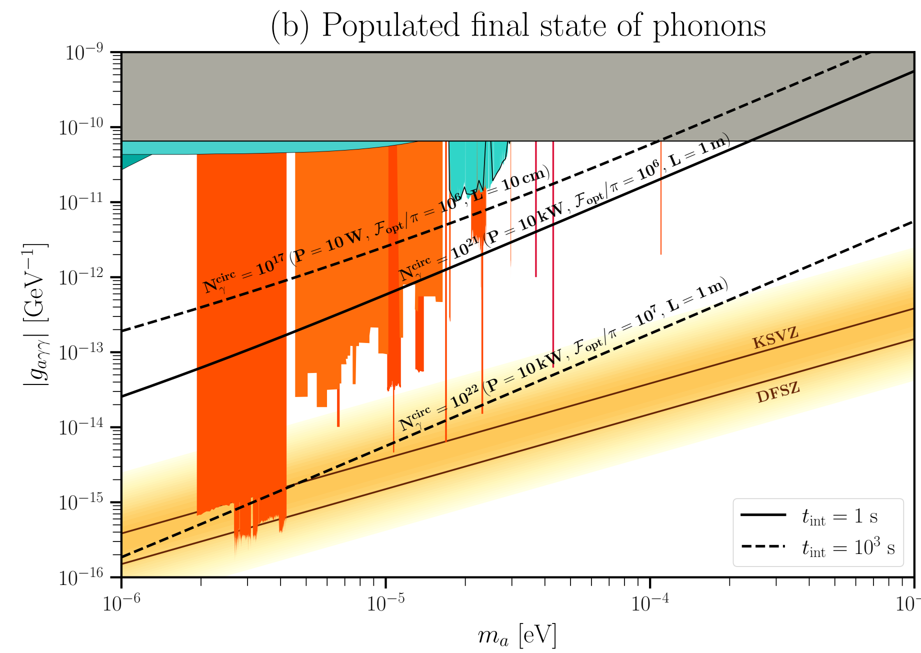


# OTHER APPLICATIONS: SINGLE EXCITATION, LOW DARK COUNTS

- Axion-mediated optomechanical process




*Murgui, Wang, KZ 2211.08432*

# MOTIVATION:POWER IN LOW-ELL

- Time delay comes from dilaton fluctuations, which is literally the radius of the $S^2$ that has been integrated out
- Only gives s-wave and no PSD information
- Gives relation between modular fluctuation and K from famous "square-root E" partition function

$$Z\left[\beta\right] \approx \int_0^\infty dE_L e^{S(E_L)-\beta E_L} \approx \int_0^\infty dE_L e^{4\pi\sqrt{L\Phi_b E_L}-\beta E_L}$$

$$\langle E\rangle = -\partial_\beta \log Z[\beta] = \frac{1}{L}\frac{\Phi_h^2}{\Phi_b}$$

$$S = \log Z[\beta] + \beta\langle E\rangle = 4\pi\Phi_h$$

*no factor of d-2*

$$\langle \Delta K^2\rangle = \langle K\rangle$$

# PIXELLON FROM MODULAR FLUCTUATIONS

- Modular Fluctuations act as quantum source in Einstein equation, but it enters non-linearly in the perturbations

$$g_{\mu\nu} = \eta_{\mu\nu} + \epsilon h_{\mu\nu} + \epsilon^2 H_{\mu\nu} + \ldots,$$

$$G_{\mu\nu} = \epsilon \left[\nabla^2 h\right]_{\mu\nu} + \epsilon^2 \left(\left[\nabla^2 H\right]_{\mu\nu} - l_p^2 T_{\mu\nu}\right) + \ldots = 0$$

$$T_{\mu\nu} \sim \frac{1}{l_p^2}\left[(\nabla h)^2\right]_{\mu\nu}$$

- At leading order, Vacuum EE $\left[\nabla^2 h\right]_{\mu\nu} = 0$
- At next order, sourced by modular fluctuations $\left[\nabla^2 H\right]_{\mu\nu} = l_p^2 T_{\mu\nu}$

# PIXELLON FROM MODULAR FLUCTUATIONS

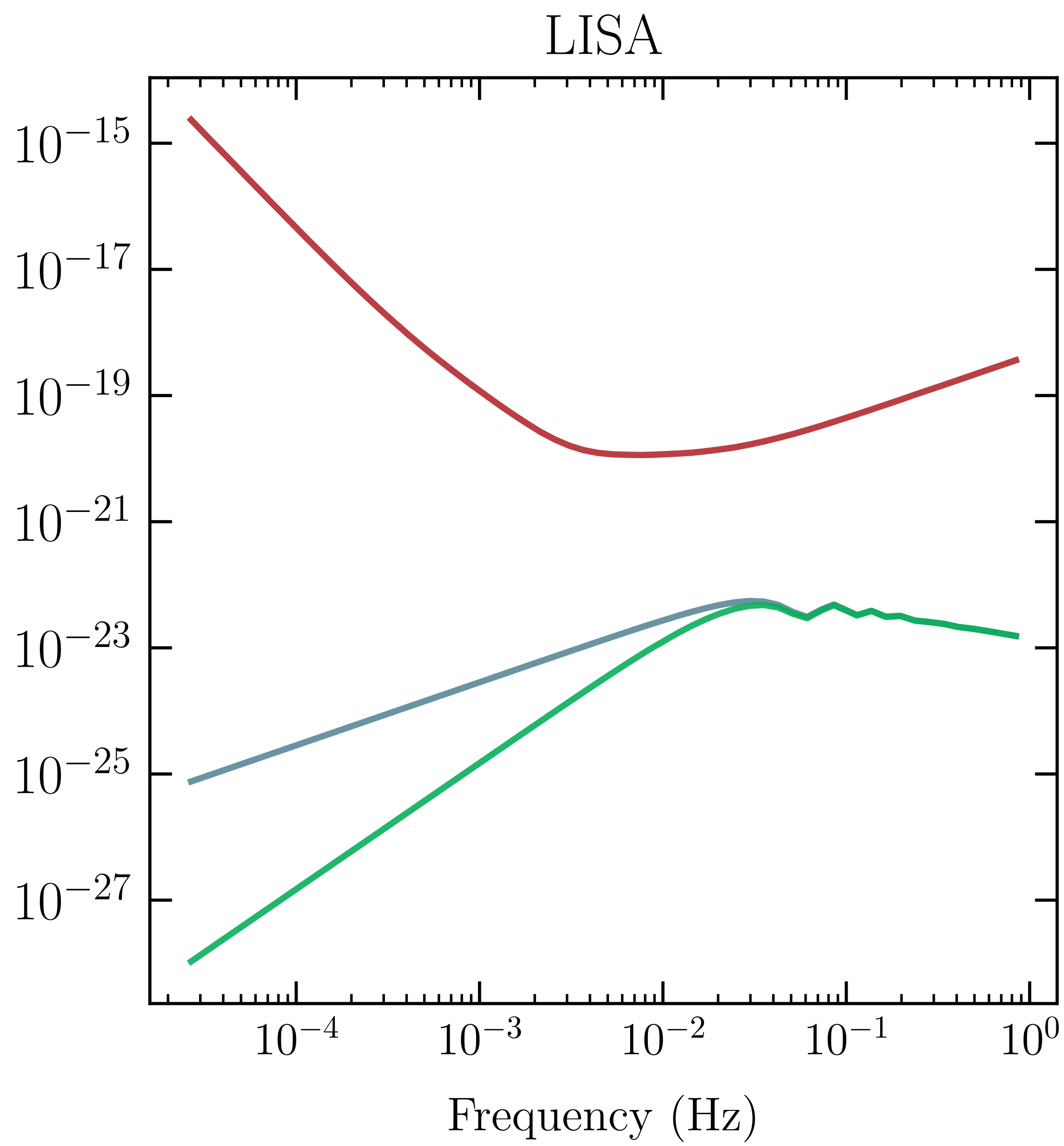
- Stress tensor vanishes in vacuum, but it does have flucts.

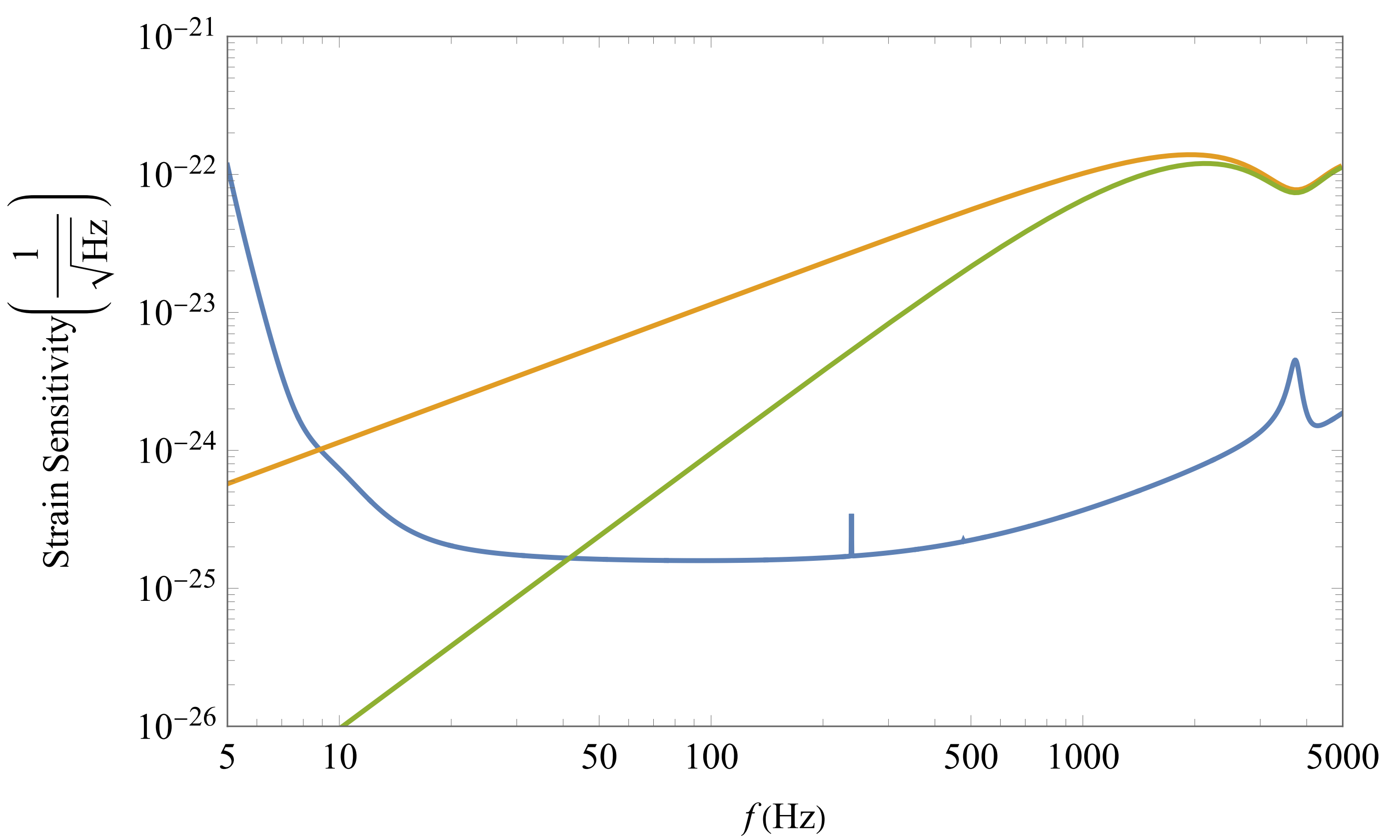
$$\langle T_{\mu\nu} \rangle \; = \; 0 \qquad\qquad \langle \Delta K^2 \rangle \sim \langle T_{\alpha\beta} T_{\mu\nu} \rangle \neq 0$$

- So leading effect enters as two point of T, or four-point of h
- Rather than compute four-point of h, can compute two-point of h with non-trivial density of states

# COMPARISON OF EXPERIMENTS

- LISA is not sensitive, but other future ground-based experiments will be overwhelmed by this signal



# EQUIVALENT PHYSICAL DESCRIPTIONS — CELESTIAL HOLOGRAPHY

- ’t Hooft commutation relations are equivalent to BMS commutations relations appearing in celestial holography

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

*’t Hooft*

*Aichelburg-Sexl*

$$ds^2 = -du^2 - 2du\,dr + 2r^2\gamma_{z\bar{z}}dz\,d\bar{z} + \big(2\partial_z X_u\,du\,dz + \text{c.c.}\big)$$

*Bondi*

$$\begin{aligned} ds^2 &= -du^2 + 2du\,dr + 2r^2\gamma_{z\bar{z}}dz\,d\bar{z} \\ &+ \frac{2m_B(u,z,\bar{z})}{r}du^2 + \big(rC_{zz}(u,z,\bar{z})dz^2 + \text{c.c.}\big) + \big(D^z C_{zz}(u,z,\bar{z})du\,dz + \text{c.c.}\big) + \cdots\,, \end{aligned}$$

$$[C(z,\bar{z}), C_{ww}(u', w, \bar{w})] = 4iGD_w^2\big(S\log|z-w|^2\big)$$

*BMS*

*He, Raclariu, KZ in progress*

# WHY DON'T YOU JUST DO A SEMICLASSICAL CALCULATION?

- Of what? Highly non-local observable.
- Propose length operator

$$L \equiv \int ds \equiv \int d\lambda \, \sqrt{g_{\mu\nu}\dot{x}^\mu \dot{x}^\nu}$$

- Compute two-point function of length operator
- Leading contribution to 2-pt is 4-pt in length fluctuations

$$L = L^{(0)} + \epsilon L^{(1)} + \epsilon^2 L^{(2)} \qquad\qquad L^{(0)}|_\gamma = 0, \quad L^{(1)}|_\gamma = 0$$

*He, Sivaramakrishnan, KZ in progress*