Theory/Experiment Collaboration and GQuEST

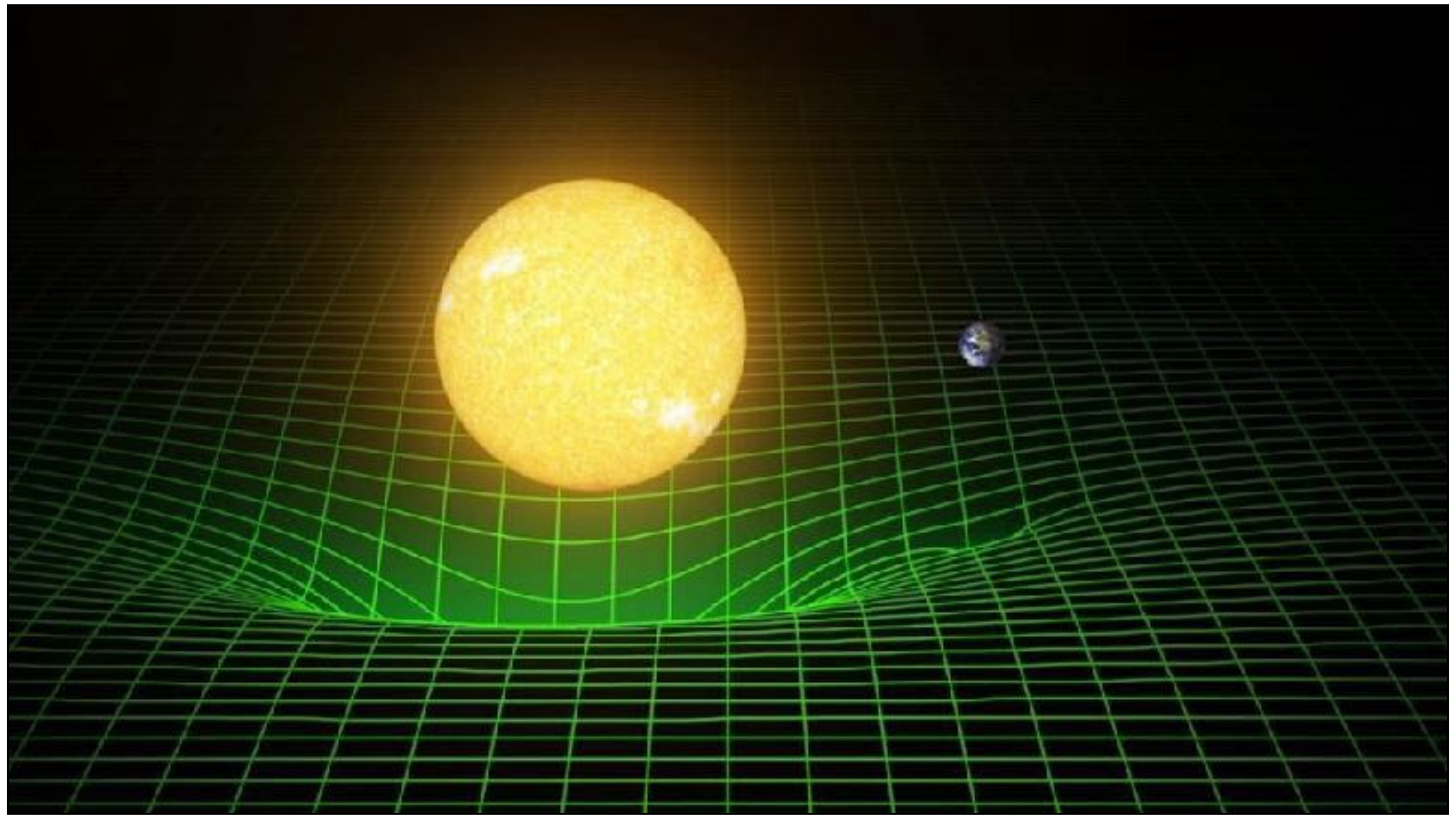
UV Effects of QG in the IR

Kathryn Zurek,FNAL-GQuEST Internal Review

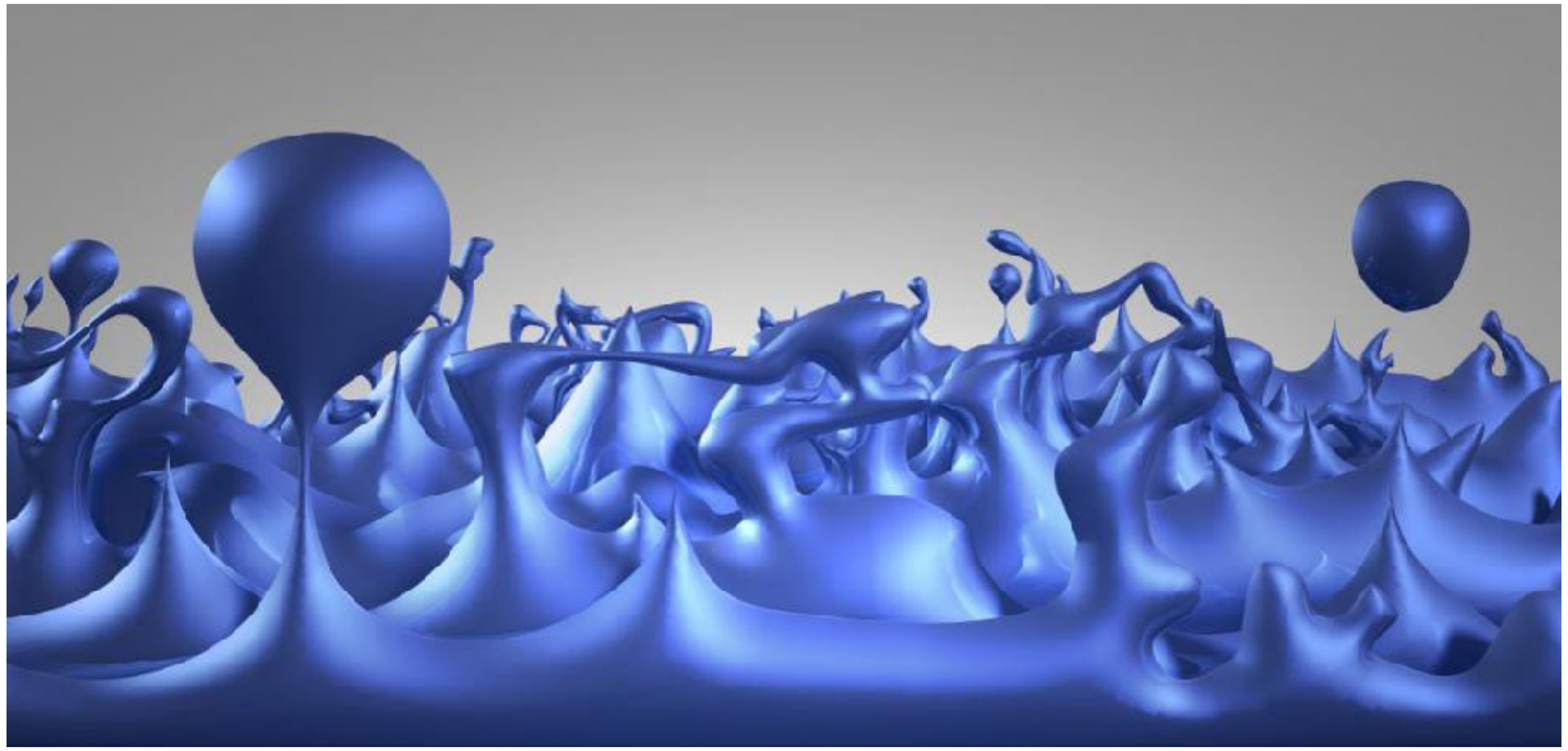
Quantum Gravity

Spacetime Fluctuates and has Fundamental Uncertainty

Classical



Quantum

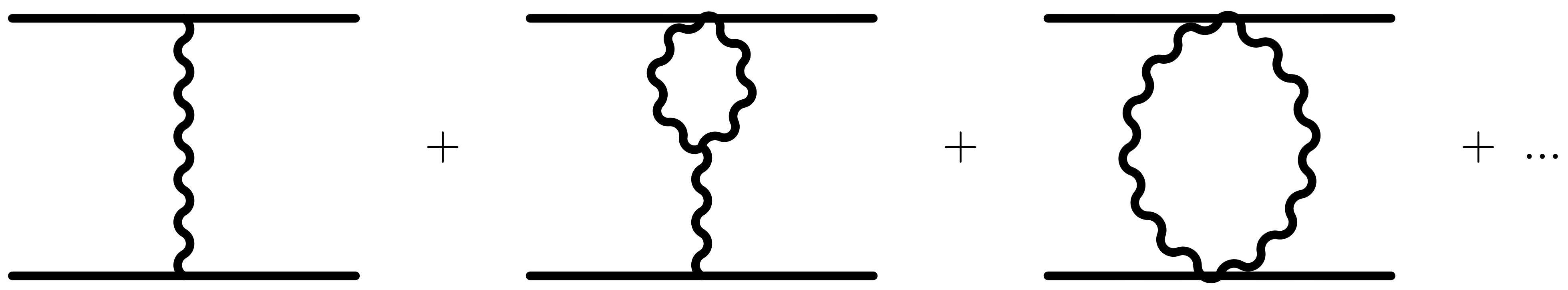


$$l_p \sim 10^{-35}\ \mathrm{m} \sim 10^{-43}\ \mathrm{s}$$

Perturbatively, there should be no observational effects

Leads to very strong theoretical prior

- From usual EFT reasoning:



$$V(r) = -\frac{Gm_1m_2}{r}\left(1 + a\frac{G(m_1+m_2)}{rc^2} + b\frac{G\hbar}{r^2c^3}\right)$$

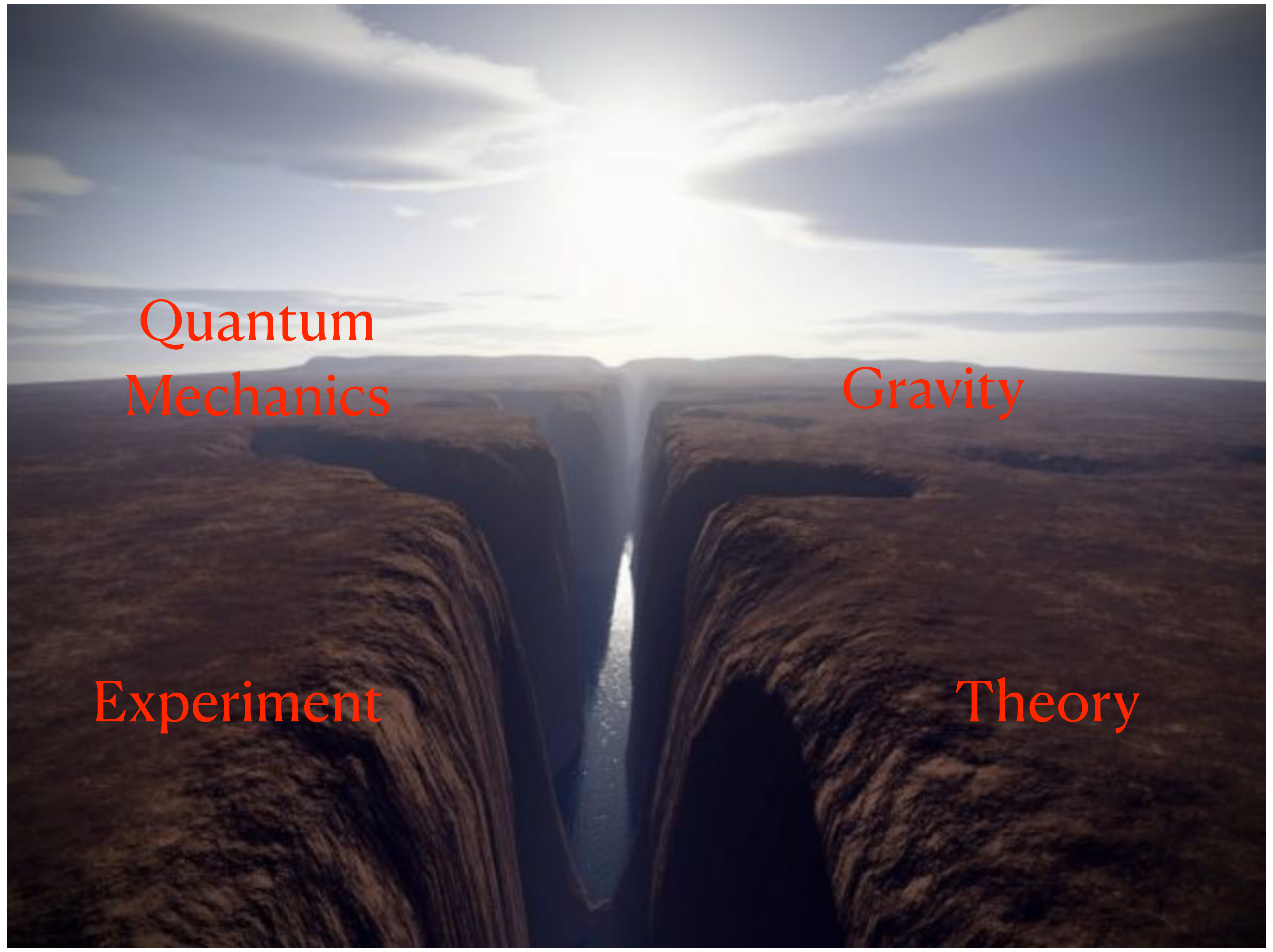
Donoghue, lecture notes on QG as EFT

- 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
- Any observable should be "analytic" in coupling constant G

Quantum Gravity and Its Observational Signatures

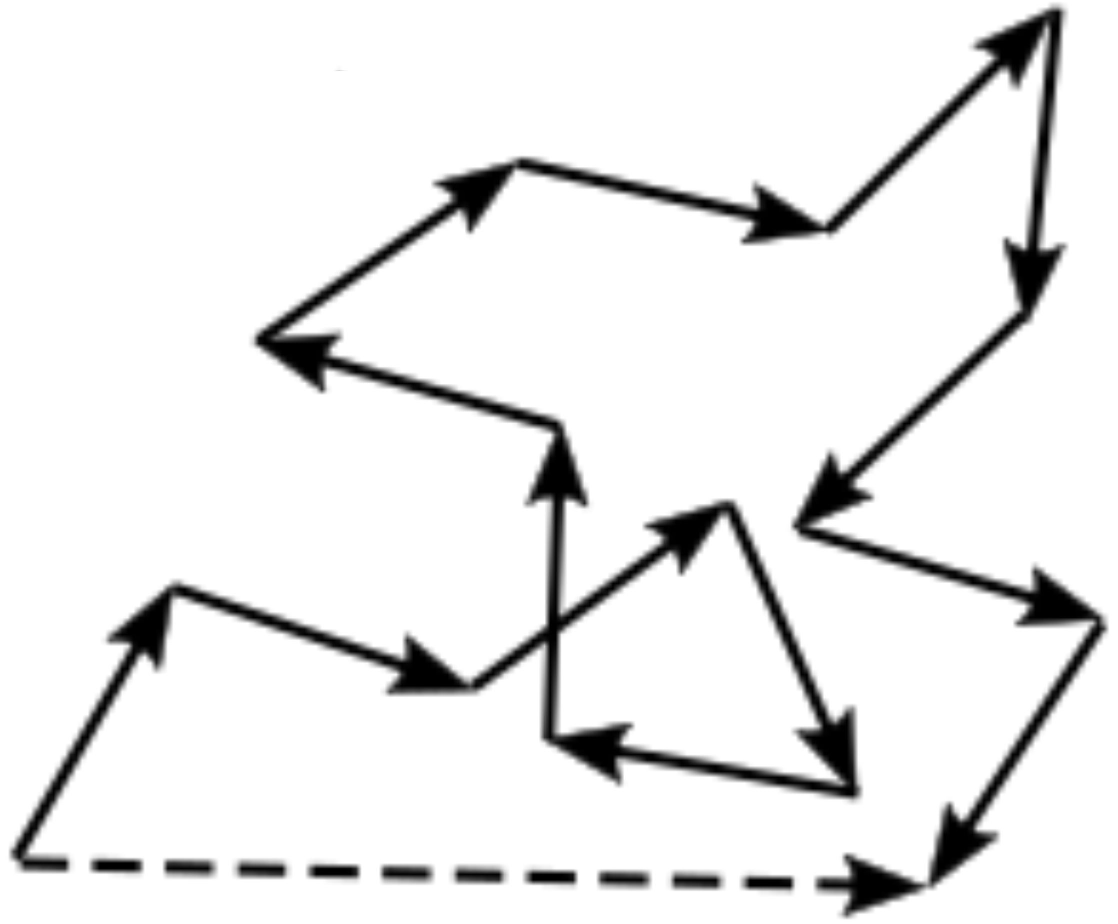
QuRIOS

- Conventional wisdom is that quantum gravity is not observable and therefore the divide between theory and experiment is natural
- New results suggest that the conventional wisdom may not be correct
- New experimental tools open new ways to test hypotheses
- Note that we are approaching this from the point of view of "conventional" QG



Brownian Noise

UV effects can be transmuted in infrared



$$\Delta t = R/v$$

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

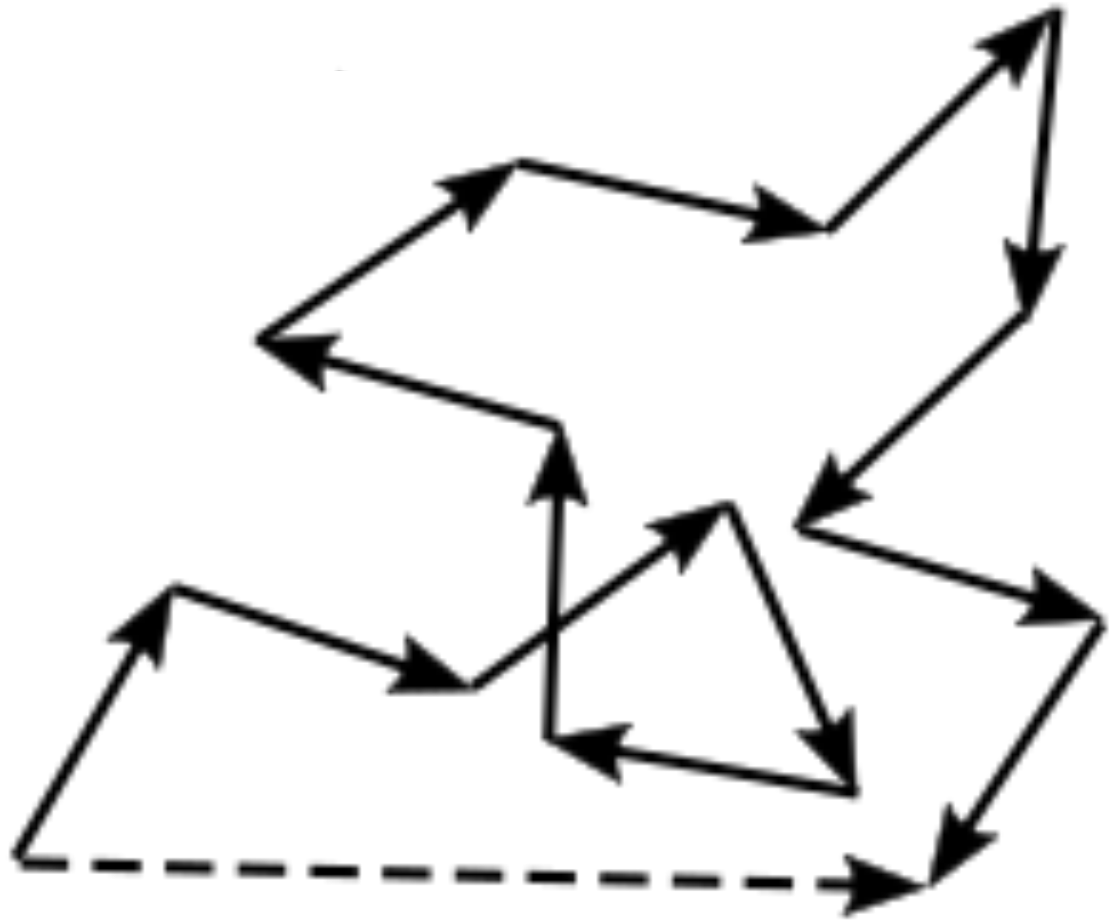
$D \sim \Delta t$ Observing Time

UV Scale IR Scale

Brownian Noise

UV effects can be transmuted in infrared

N = Number of times particle interacts



$$\Delta t = R/v$$

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

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

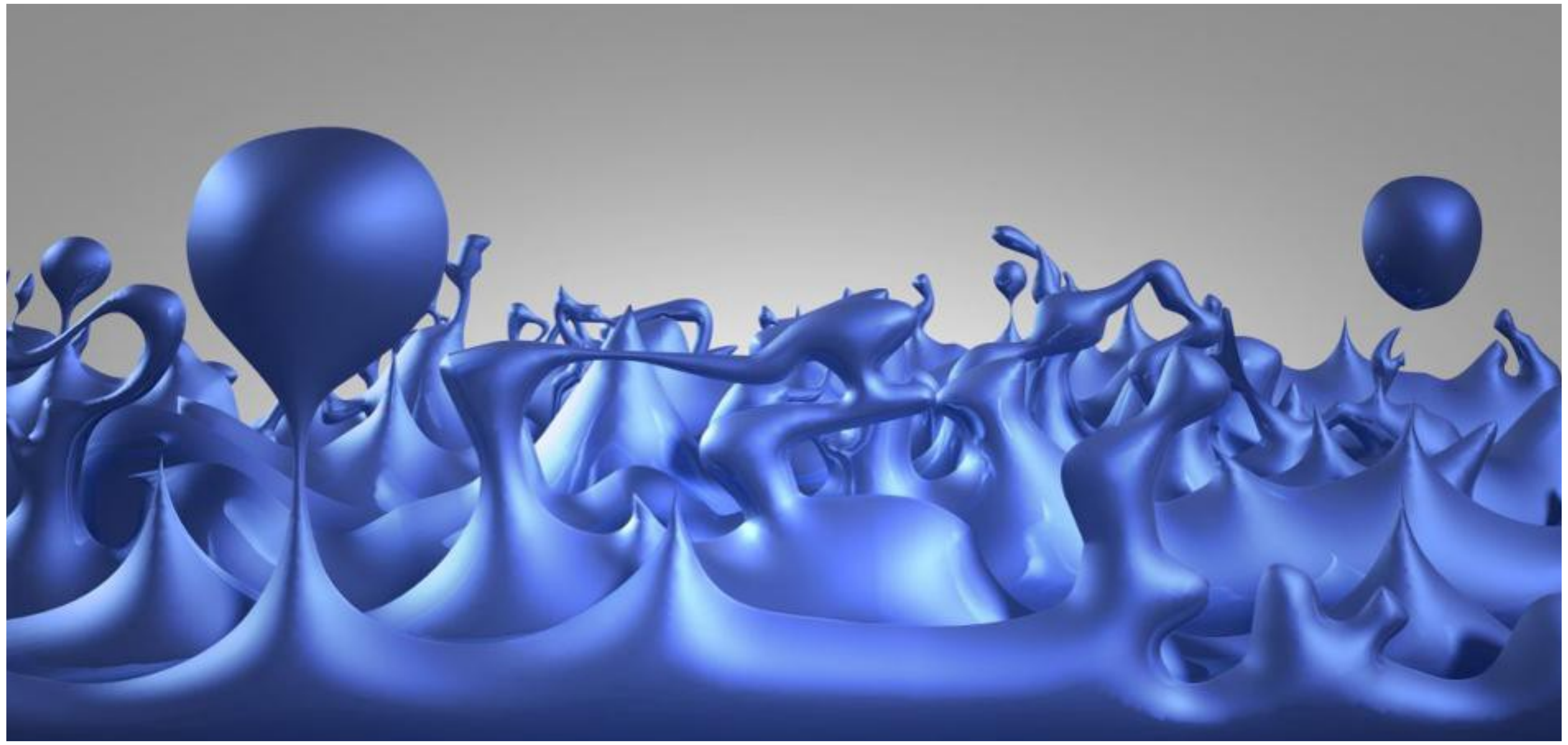
Diffusion is simply random walk or “root-N” statistics

Quantum Gravity

—> Fluctuations in Spacetime

OLD VIEW: VISIBLE ONLY AT SHORT DISTANCES

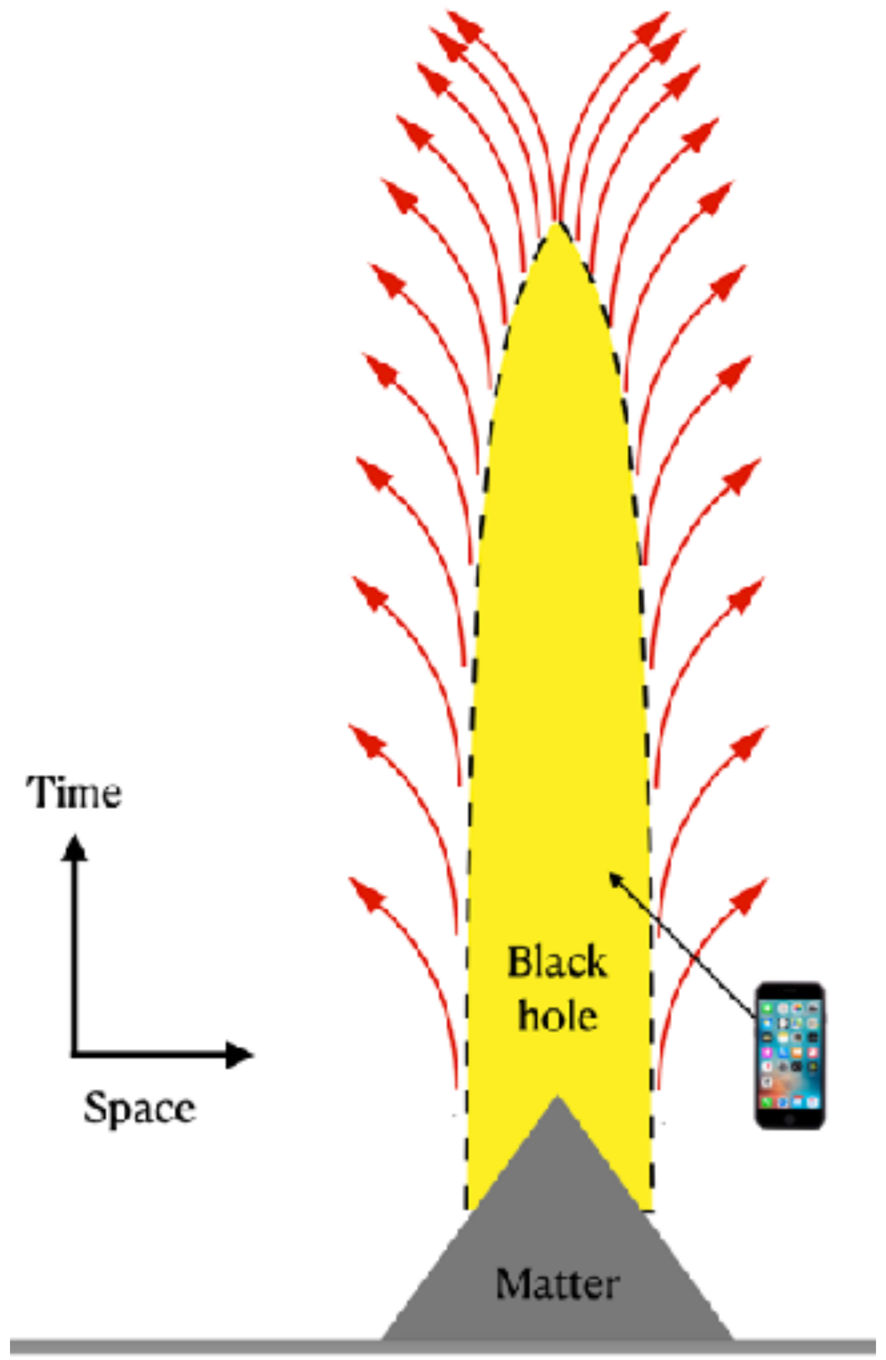
NEW VIEW: INFRARED EFFECTS ARE IMPORTANT



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

Black Holes Sharpen the QM / Gravity Divide

Information Loss



Throw matter into black hole.

Information is lost according to gravity.

But information can't be lost by QM.

New View: Non-Locality and Entanglement Play a Role

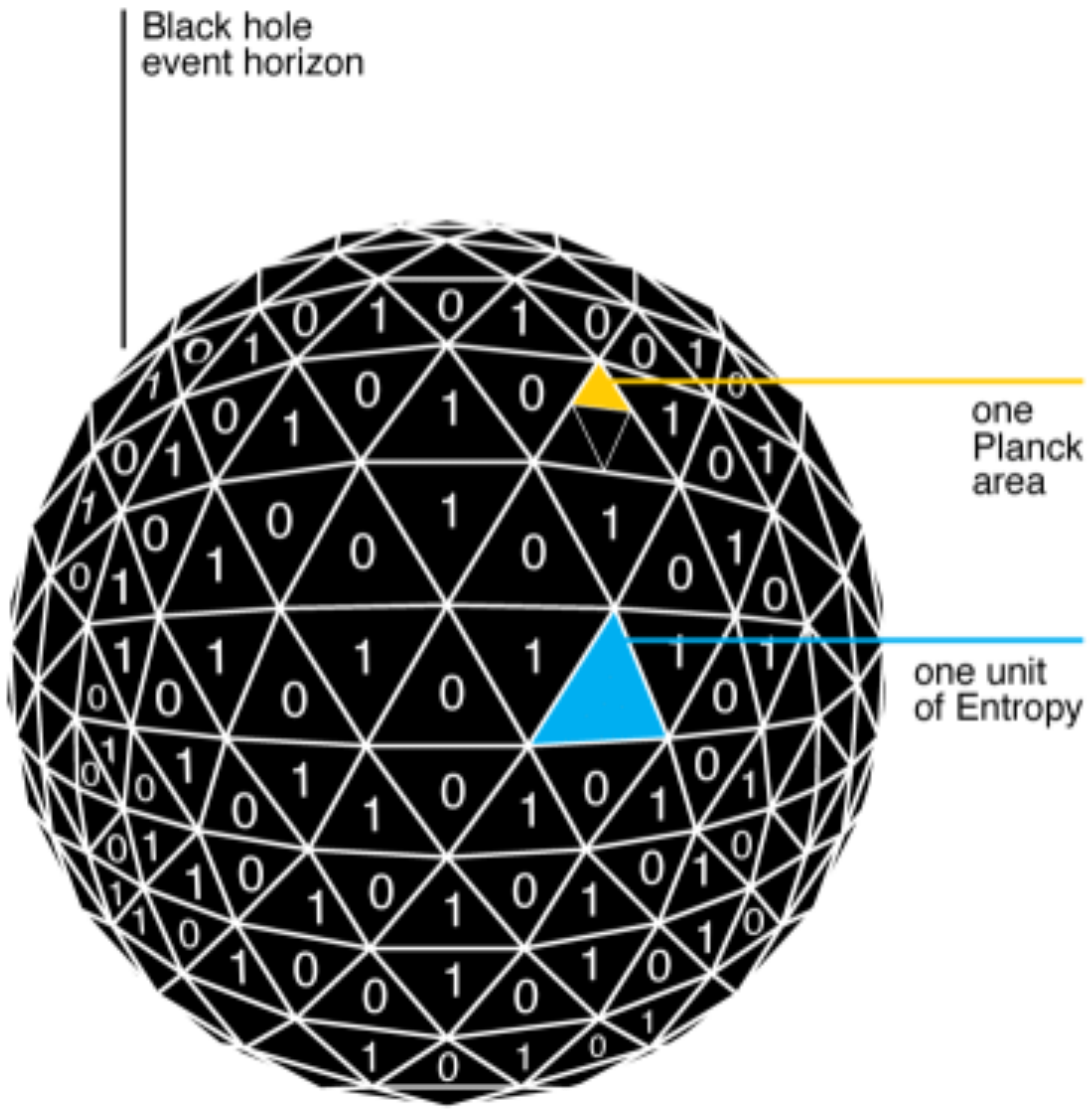
Thermodynamics of Black Holes

Black Holes have Entropy

Entropy of a Black Hole

=

Area of its Horizon



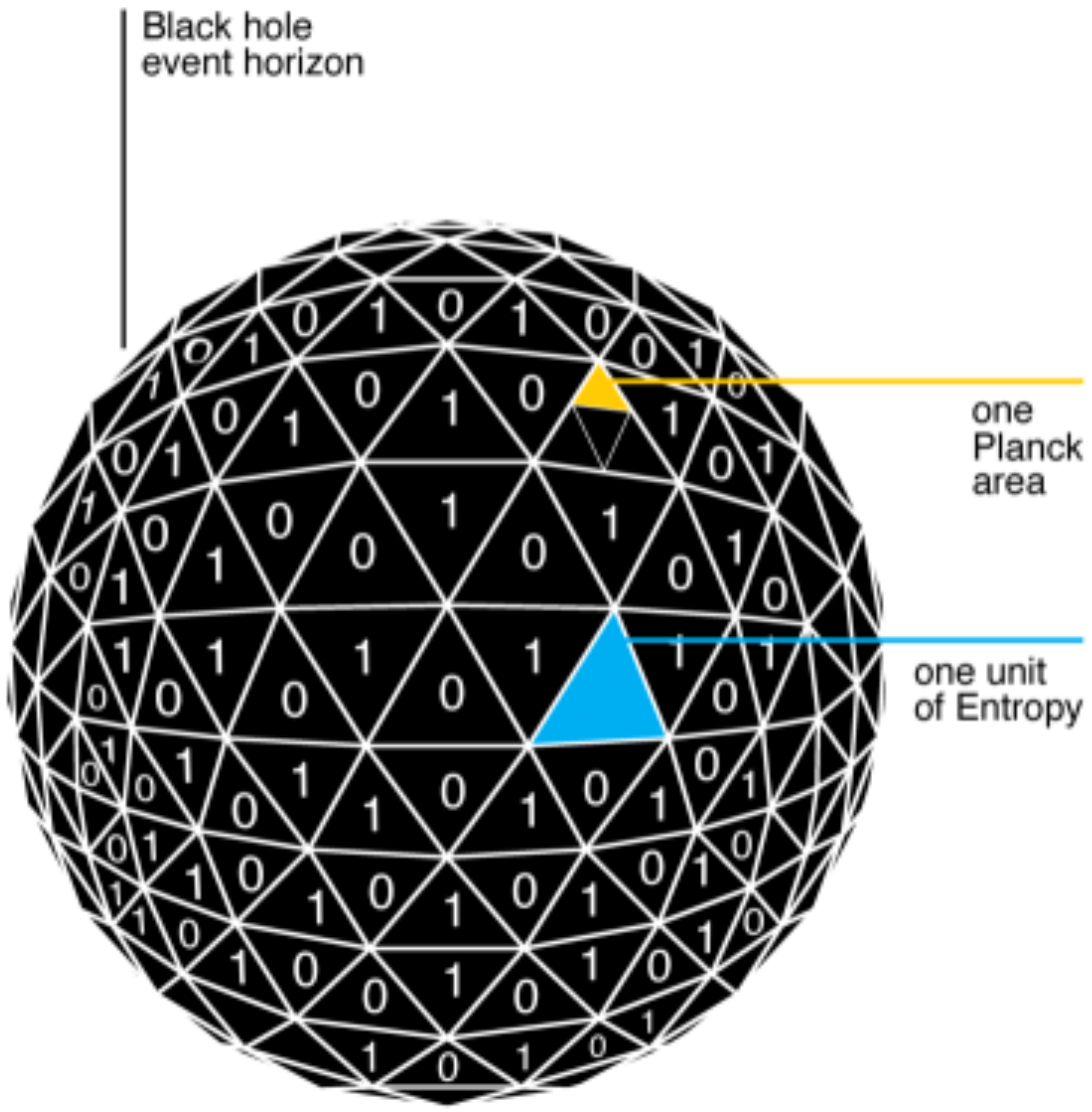
Thermodynamics of Black Holes

Black Holes have Pixels

Entropy is Information

it counts the number of bits

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

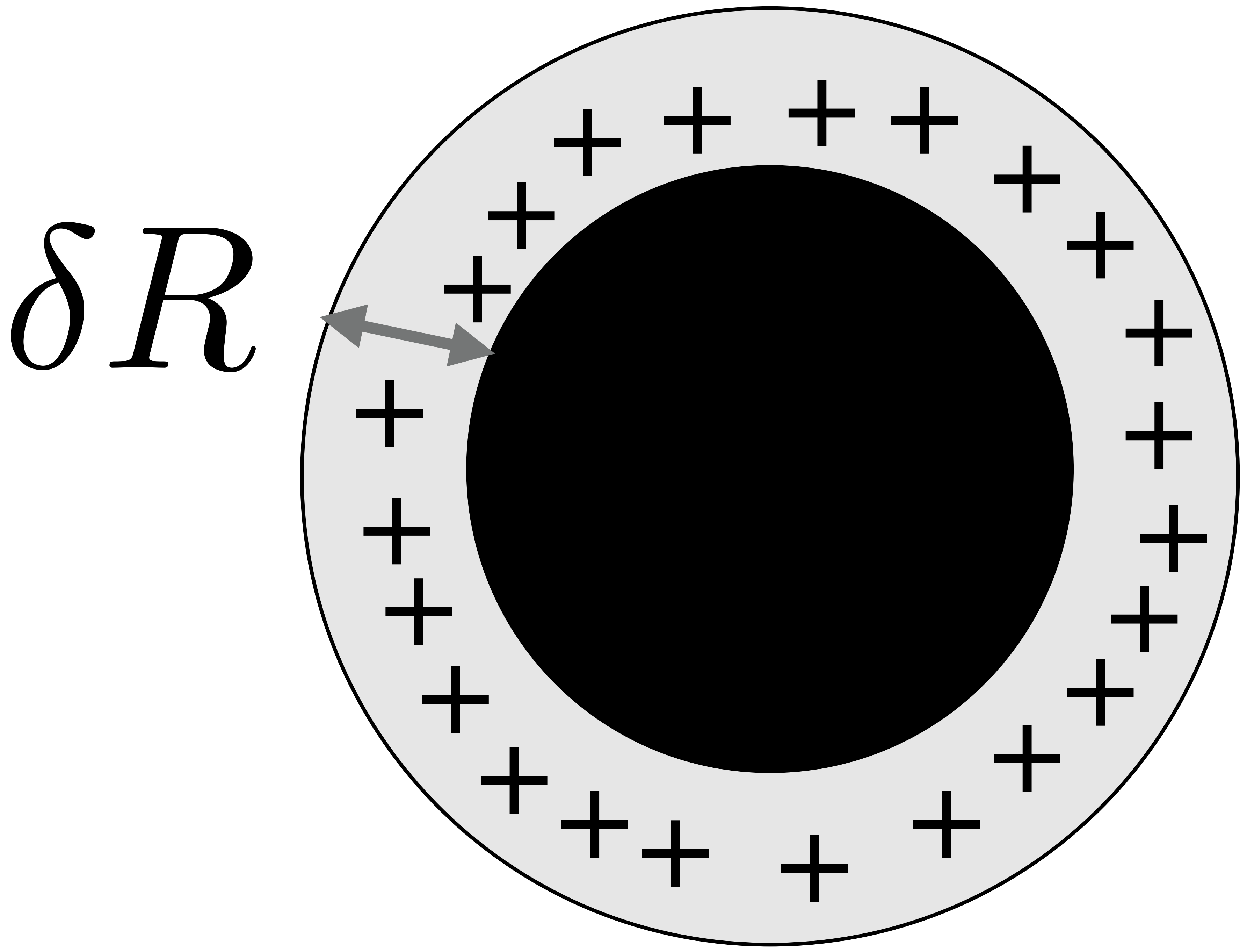


Observational Signatures of Quantum Gravity

Quantum Fuzziness at "Long" Distances

- Degrees of freedom PIXELS can fluctuate thermodynamically

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

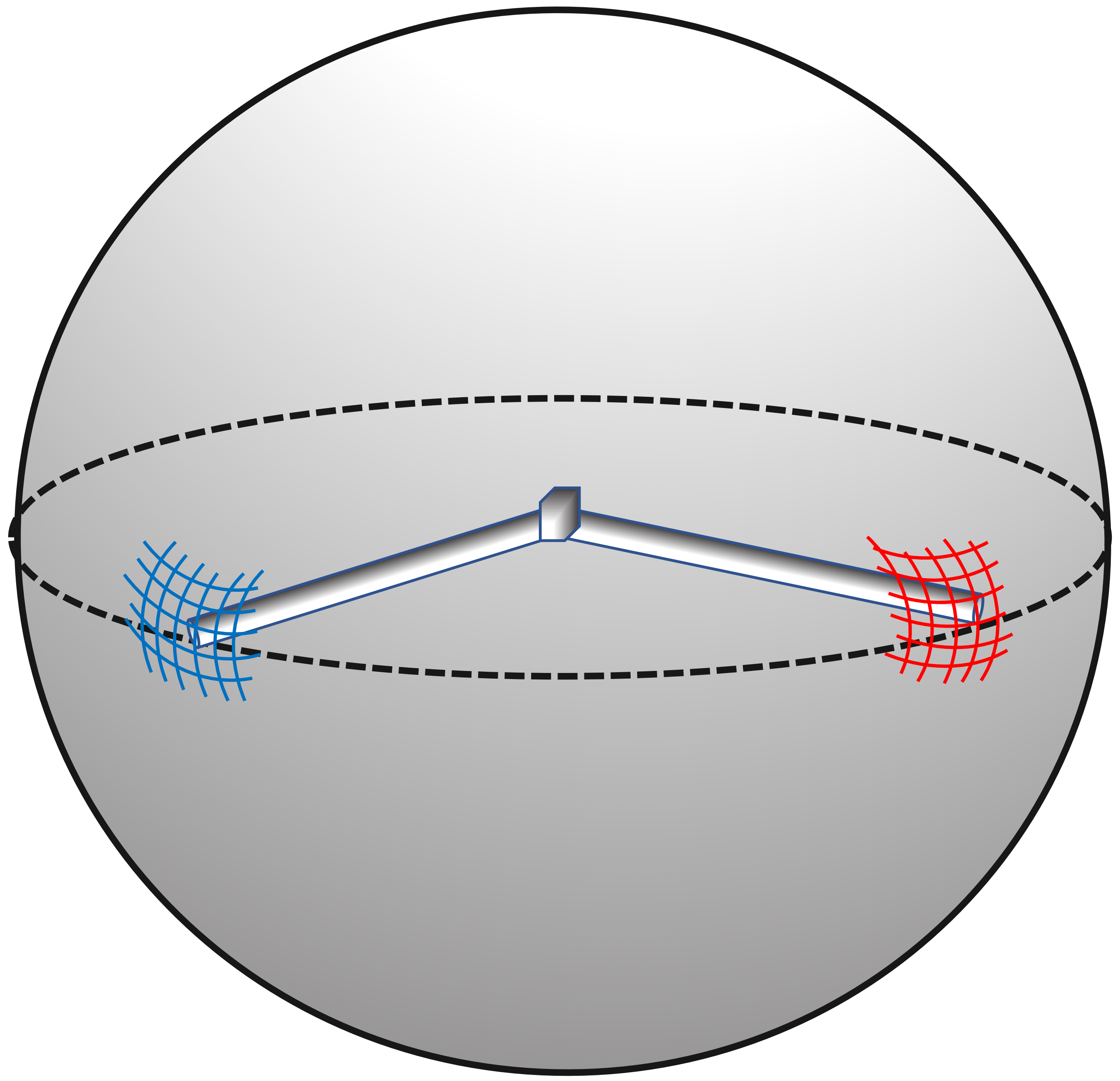


- Unobservably small in a black hole

Observational Signatures of Quantum Gravity

An Experimental Measurement Defines a Horizon

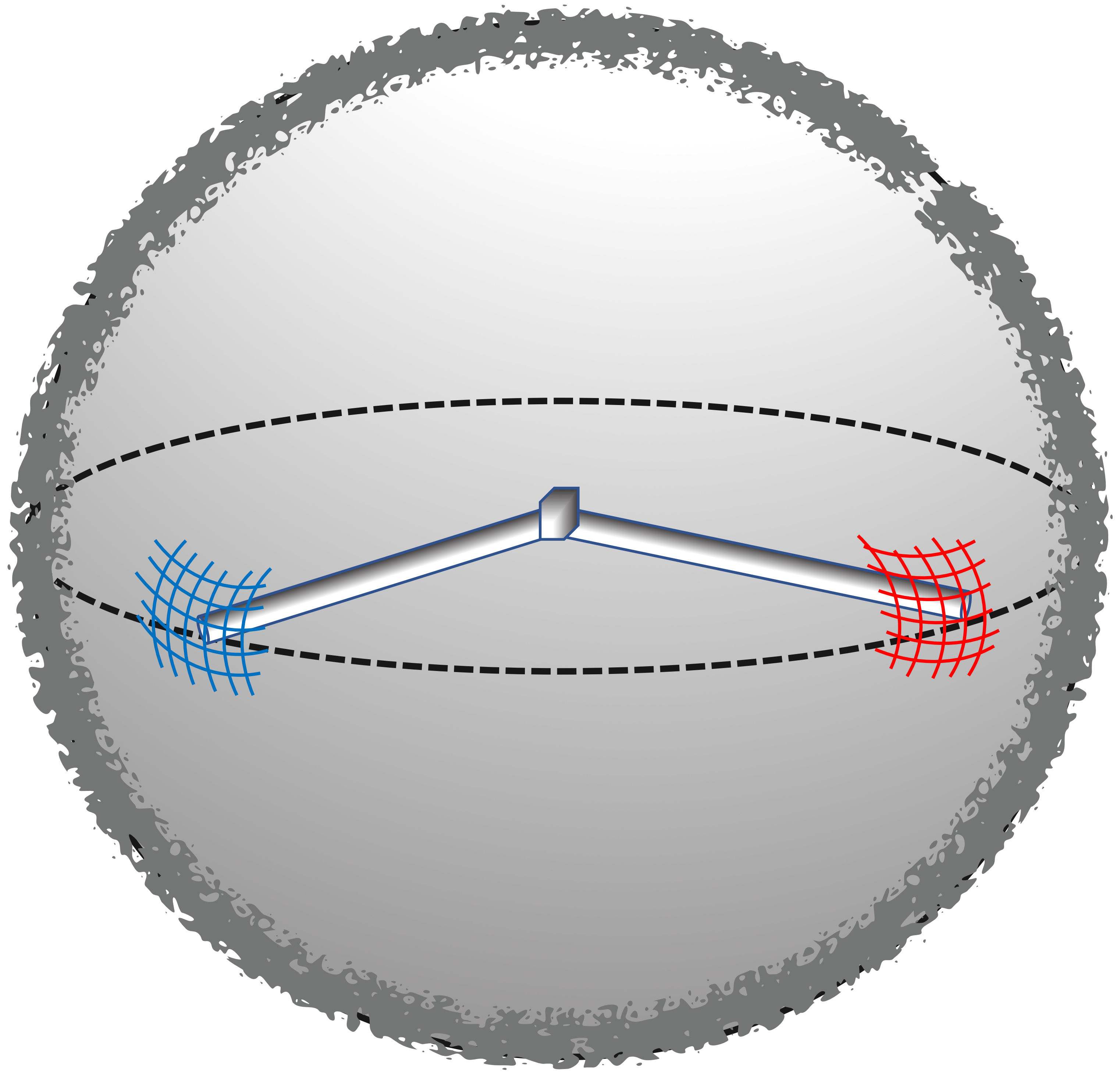
- Consider the light beams of an interferometer



What Length Fluctuations Can be Measured?

e.g. in LIGO

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



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

Parametrically the same as a quantum uncertainty of a black hole horizon

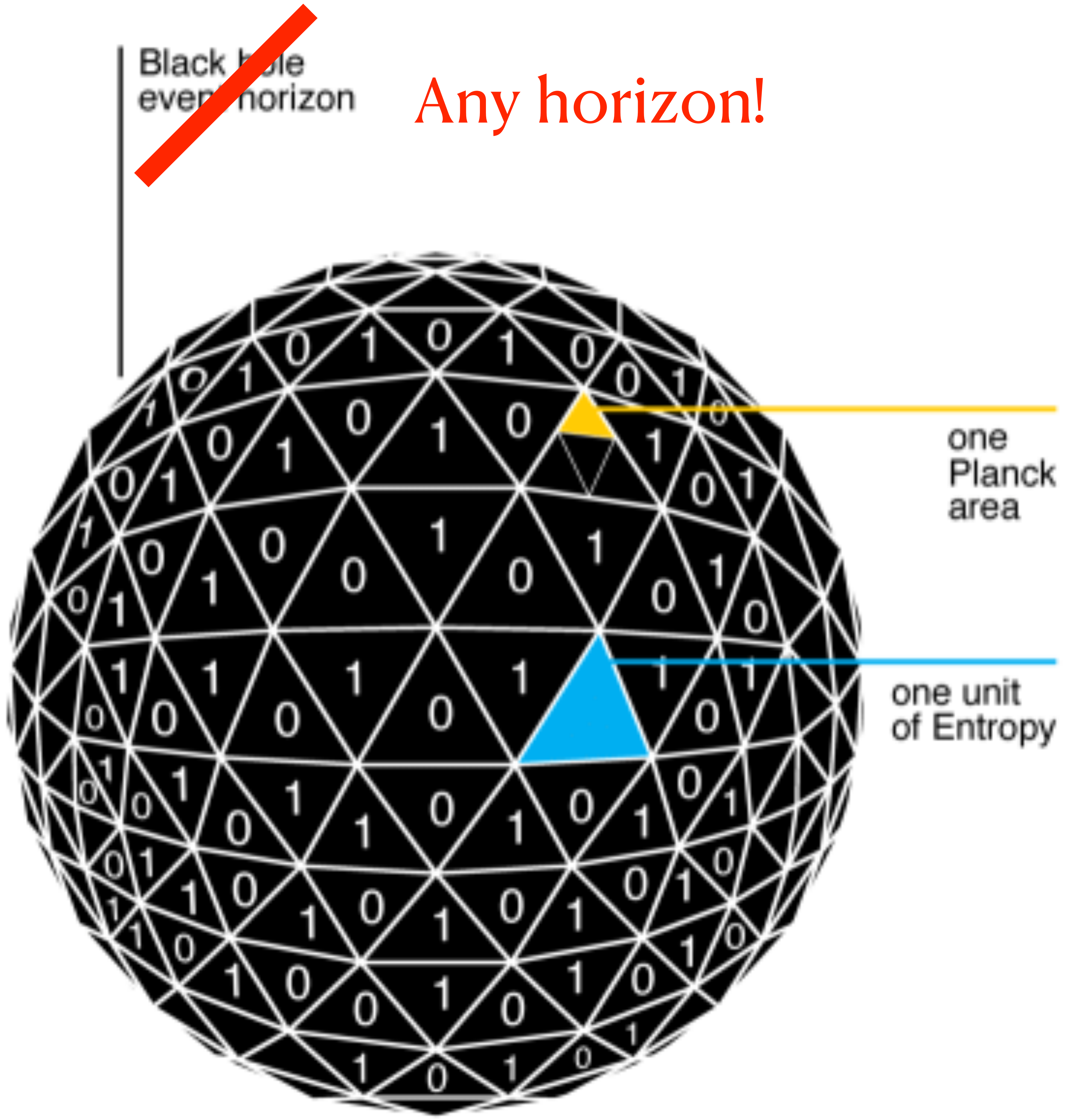
Holographic Principle

The World as a Hologram

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

- Any horizon, not just a black hole horizon!

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



Calculate Vacuum Fluctuation

Step 1

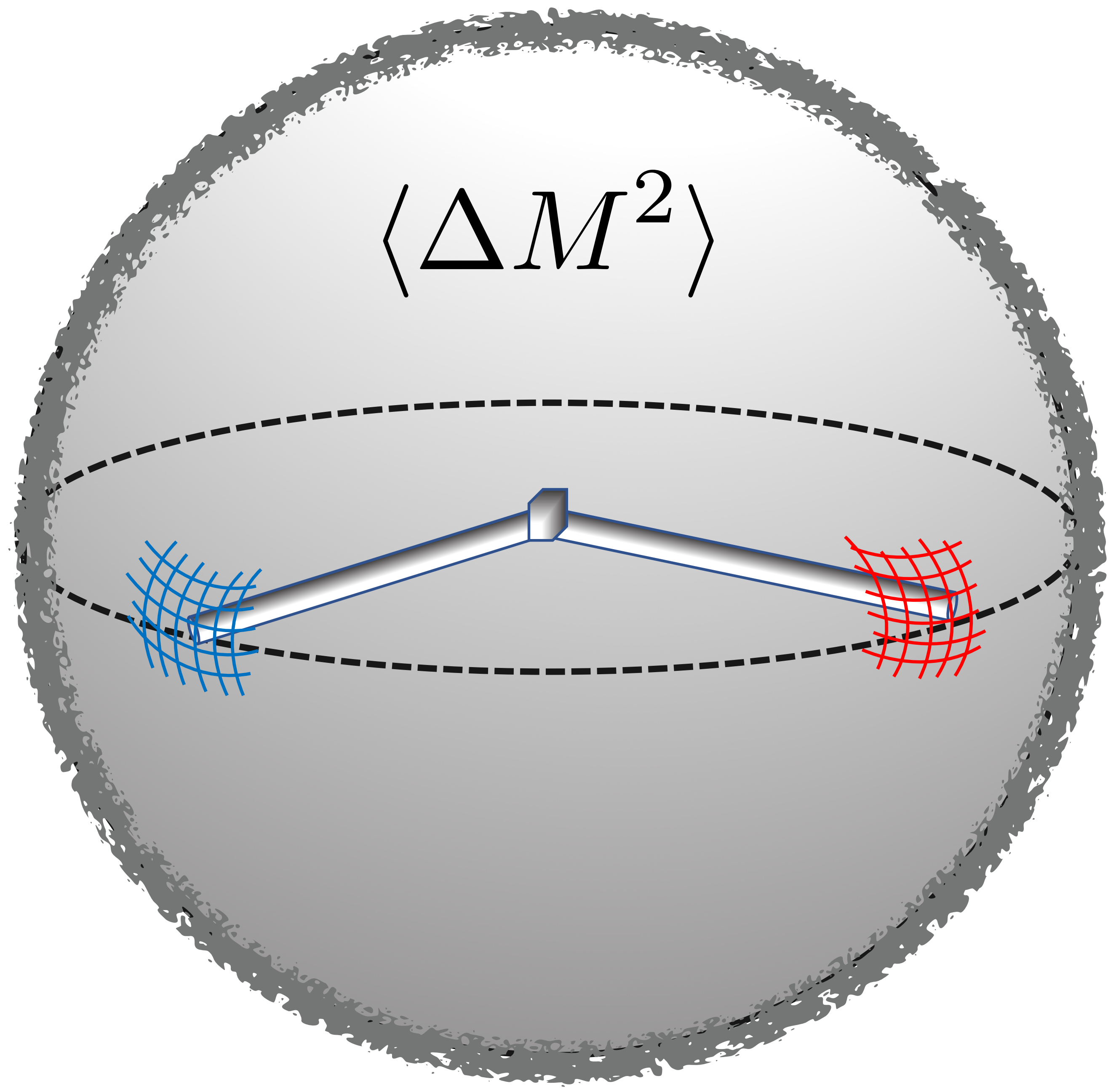
- Number of holographic degrees of freedom is the entropy

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

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

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

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



Vacuum Fluctuation Sources Metric Fluctuation

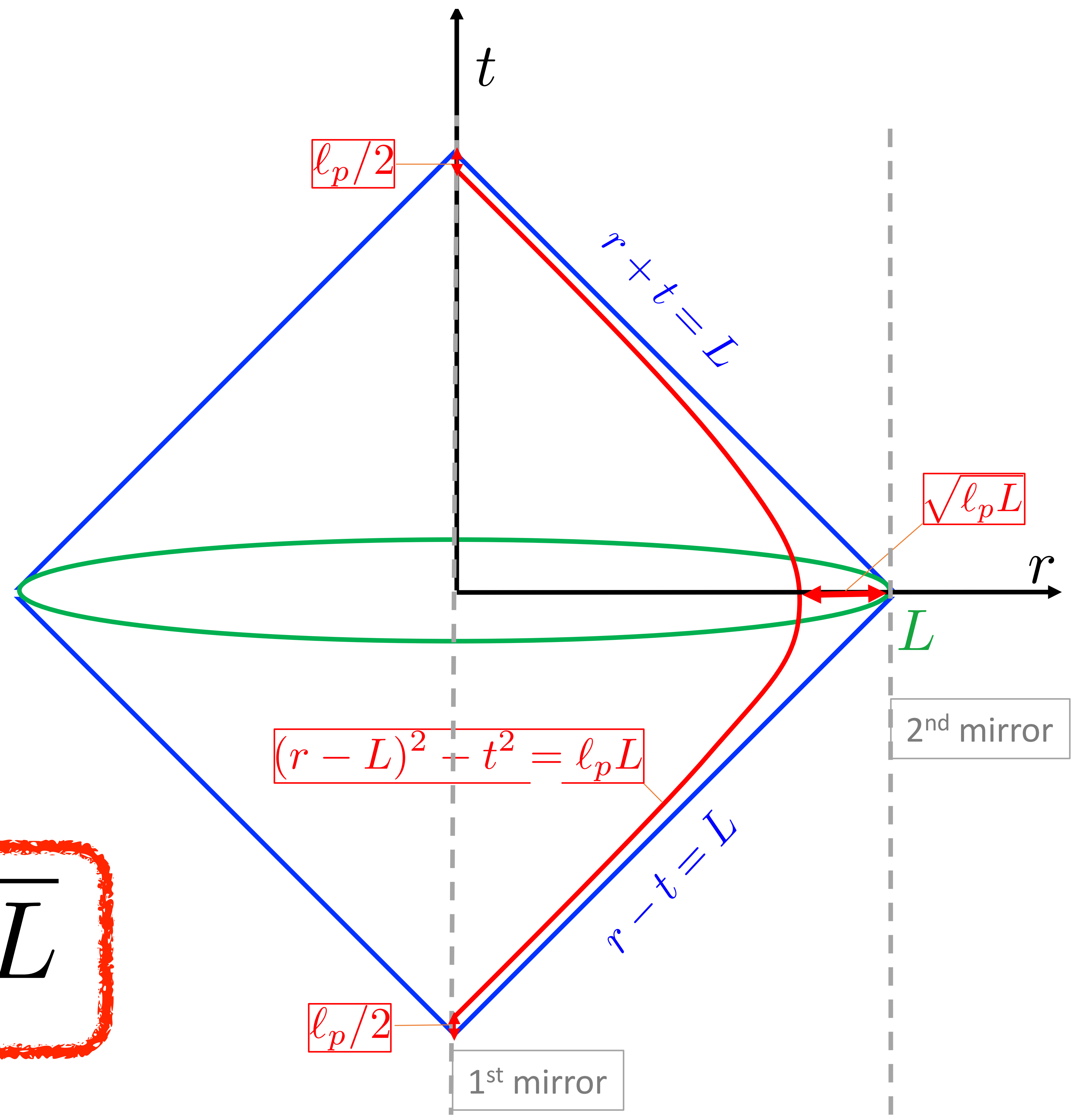
Step 2

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

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

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

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

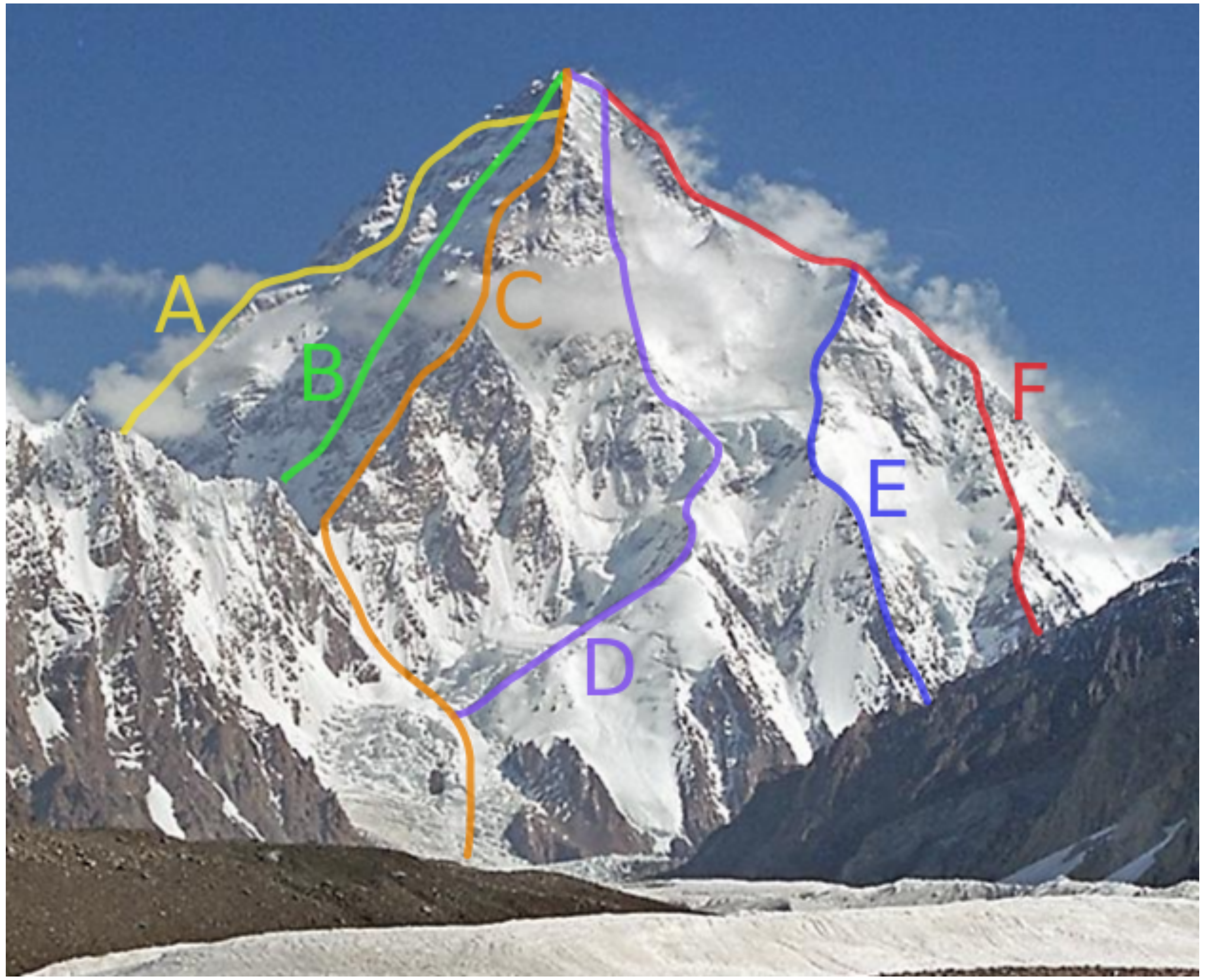


One Mountain, Many Faces

w/He,Sivaramakrishnan,Wilson

Equivalent physical descriptions

G. Length Operator



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

Results & Publications

Working through from formal results to gauge-invariant observable

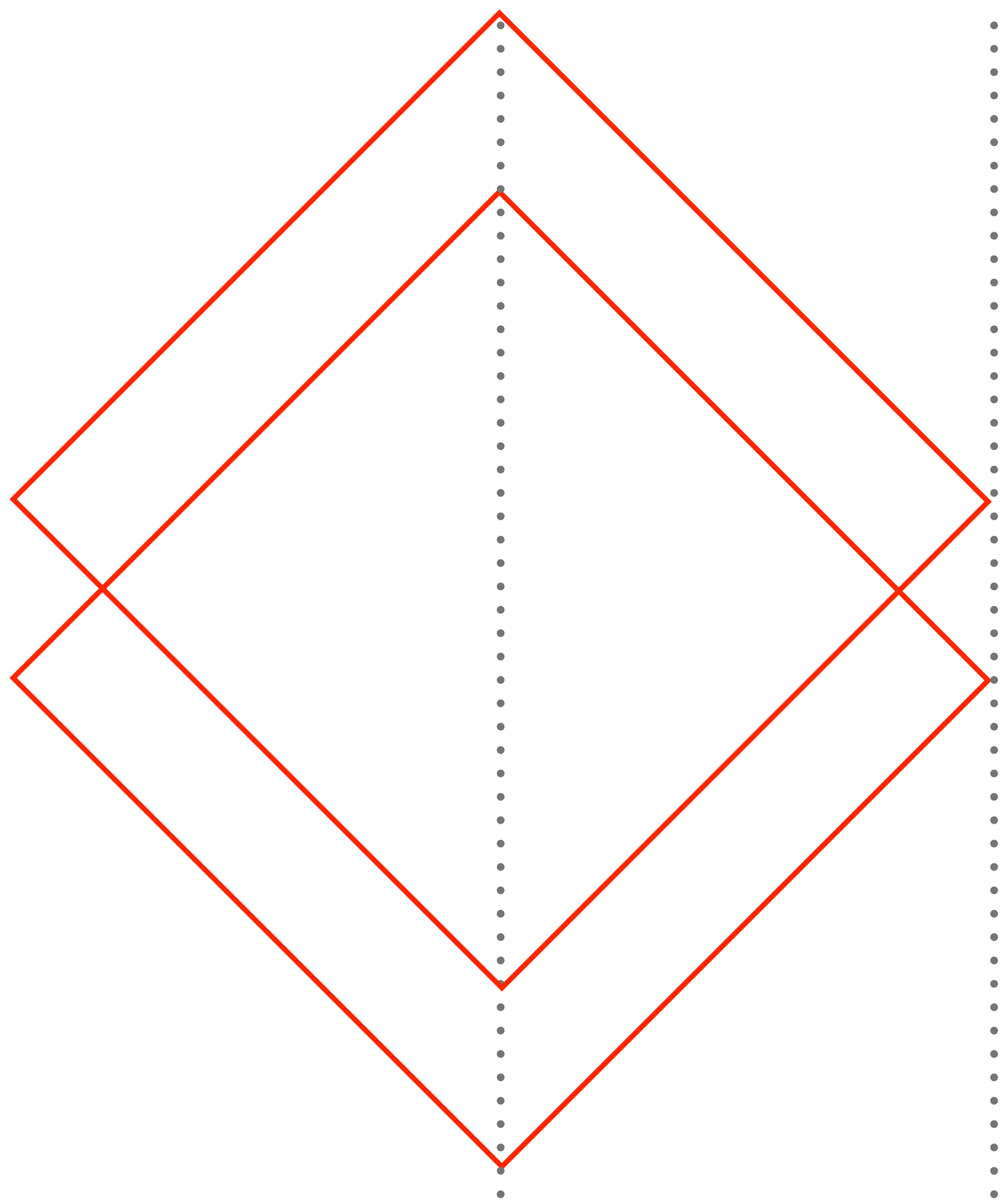
- Macroscopic Dark Matter Detection with Gravitational Wave Experiments (Du et al., 2023)
- From Shockwaves to the Gravitational Memory Effect (He et al., 2023)
- Quantum Gravity Background in Next-Generation Gravitational Wave Detectors (Bub et al., 2023)
- Stochastic Description of Near-Horizon Fluctuations in Rindler-AdS (Zhang et al., 2023)
- Interferometer response to geontropic fluctuations (Li et al., 2022)
- Modular fluctuations from shockwave geometries (Verlinde and Zurek, 2022)
- Near-horizon quantum dynamics of 4D Einstein gravity from 2D Jackiw-Teitelboim gravity (Gukov et al., 2022)
- Snowmass 2021 White Paper: Observational Signatures of Quantum Gravity (Zurek, 2022)
- Conformal description of near-horizon vacuum states (Banks and Zurek, 2021)
- On vacuum fluctuations in quantum gravity and interferometer arm fluctuations (Zurek, 2020)
- Spacetime Fluctuations in AdS/CFT (Verlinde and Zurek, 2019)
- Observational signatures of quantum gravity in interferometers (Verlinde and Zurek, 2019)

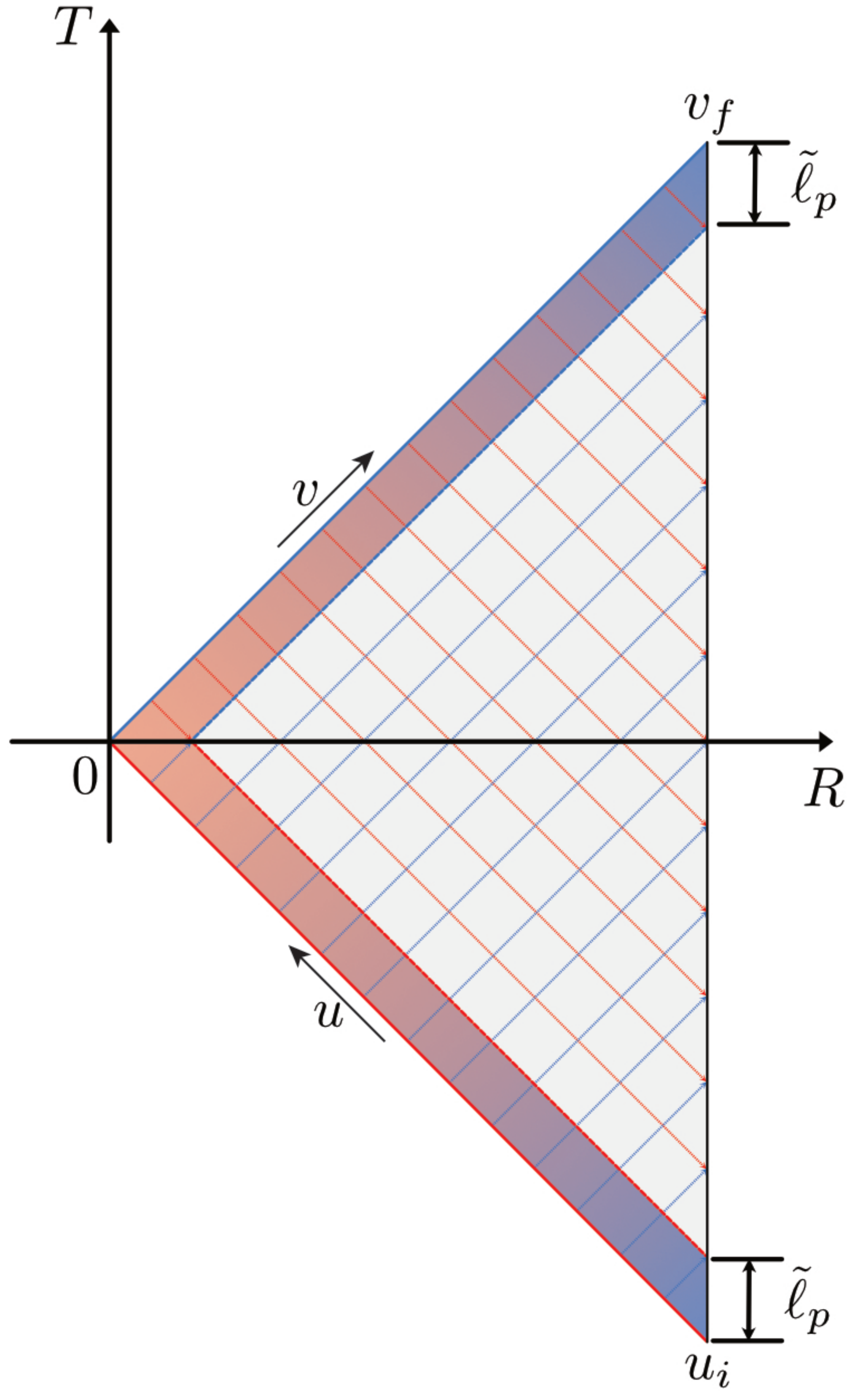
Why computing gauge invariant observables in hard

Requires knowing the global (time-dependent) metric

- At the moment we can compute, from first principles at the light-sheet horizon of a single causal diamond
- Need information of time-like trajectories of mirrors
- Correlations between causal diamonds

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





Equivalent Physical Descriptions

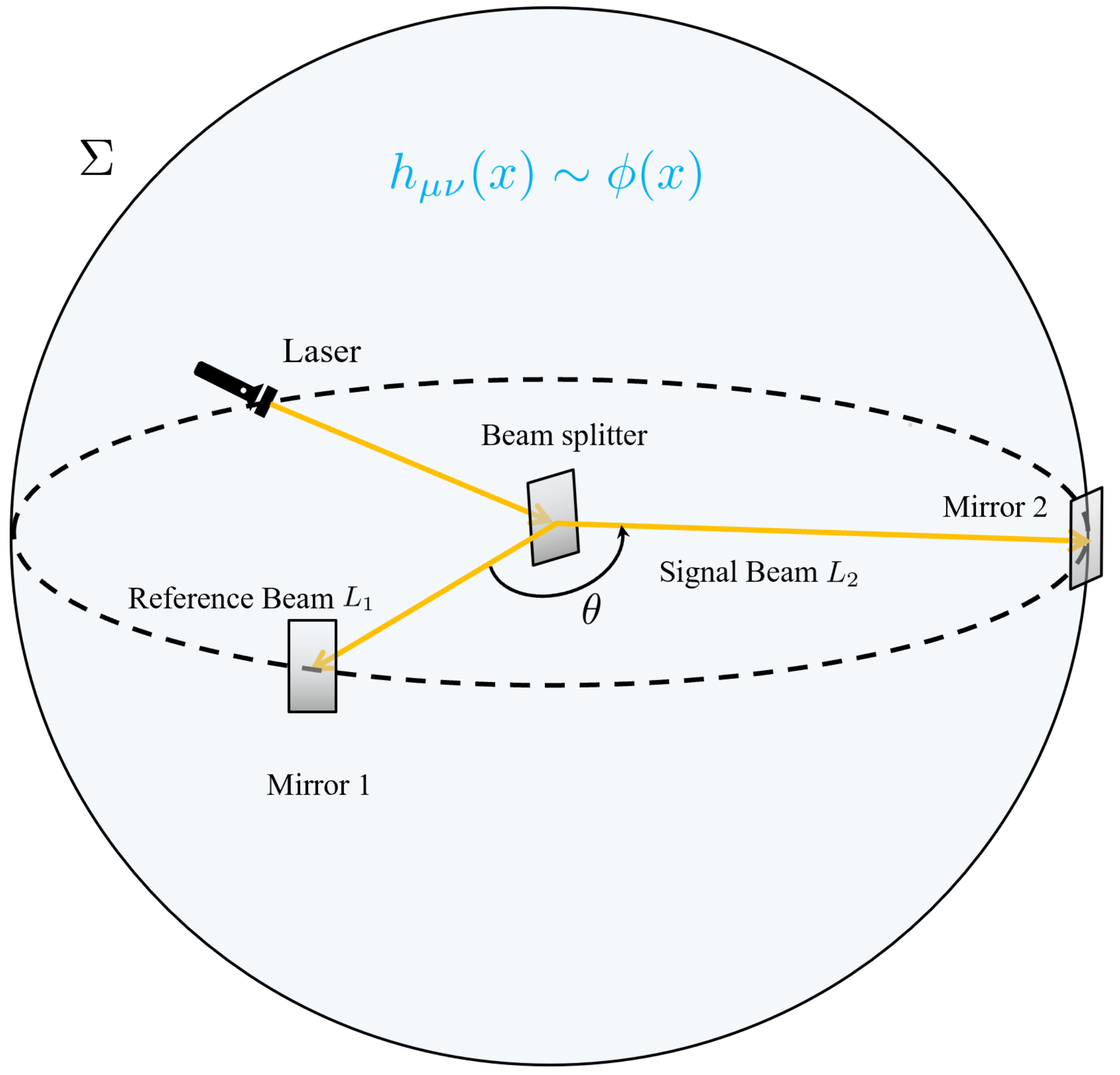
A model for pheno

- The "pixellon." *KZ 2012.05870*
- Bosonic excitation modeling hydro mode

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

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

Number of bits or "pixels"



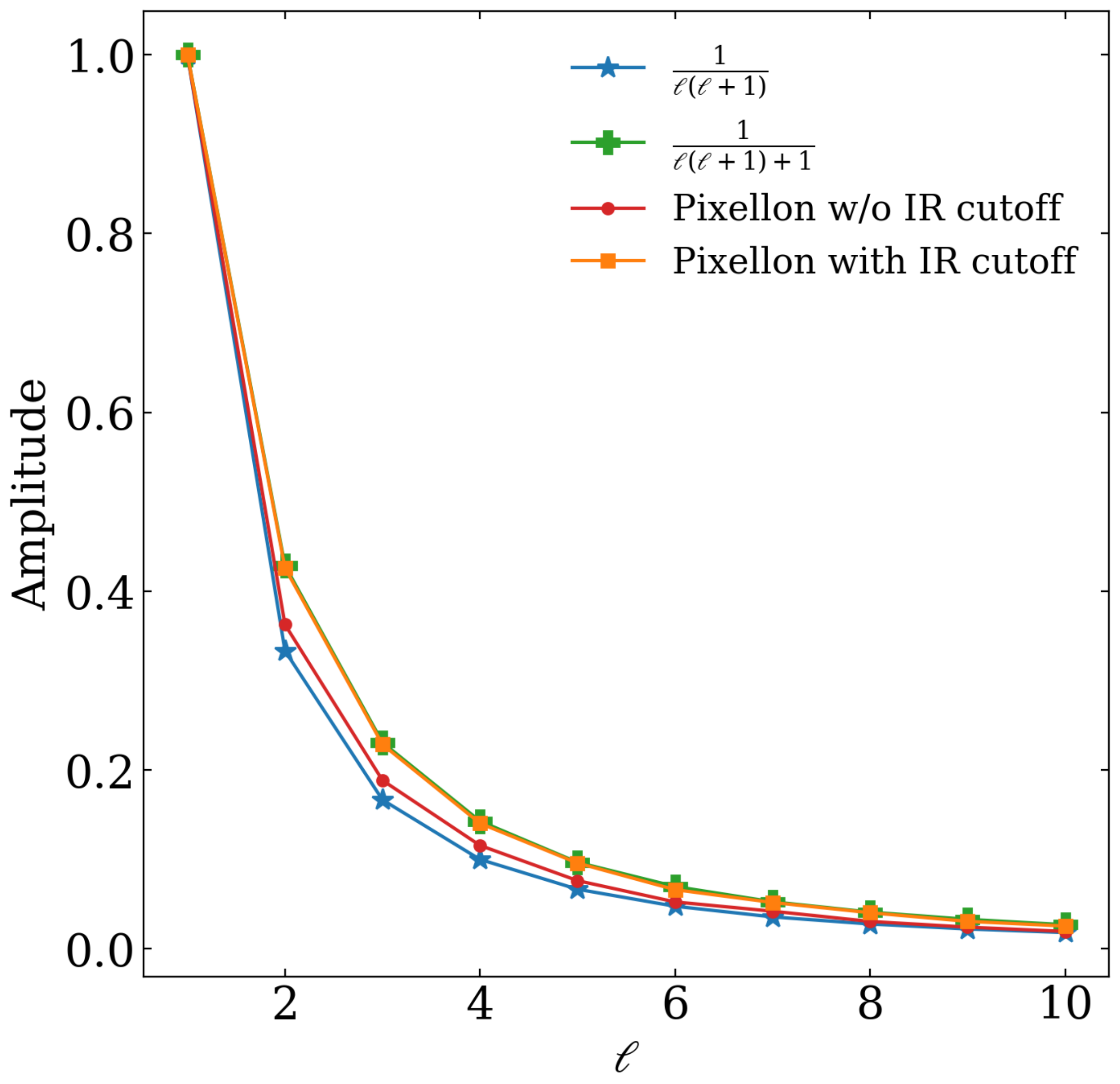
$$S_{\rm ent} = \mathcal{N} = \frac{A}{4G}$$

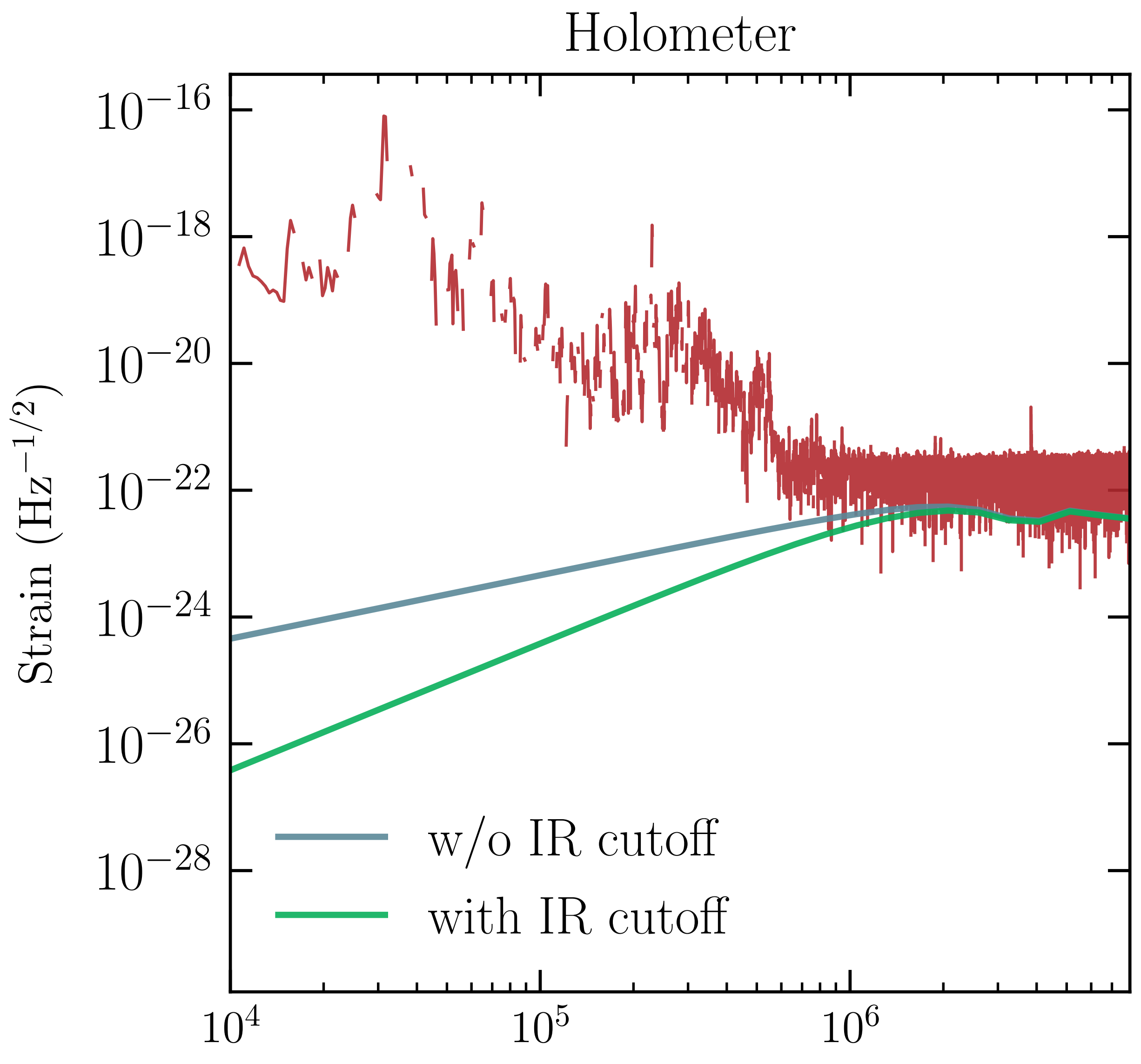
Li, Lee, Chen, KZ 2209.07543

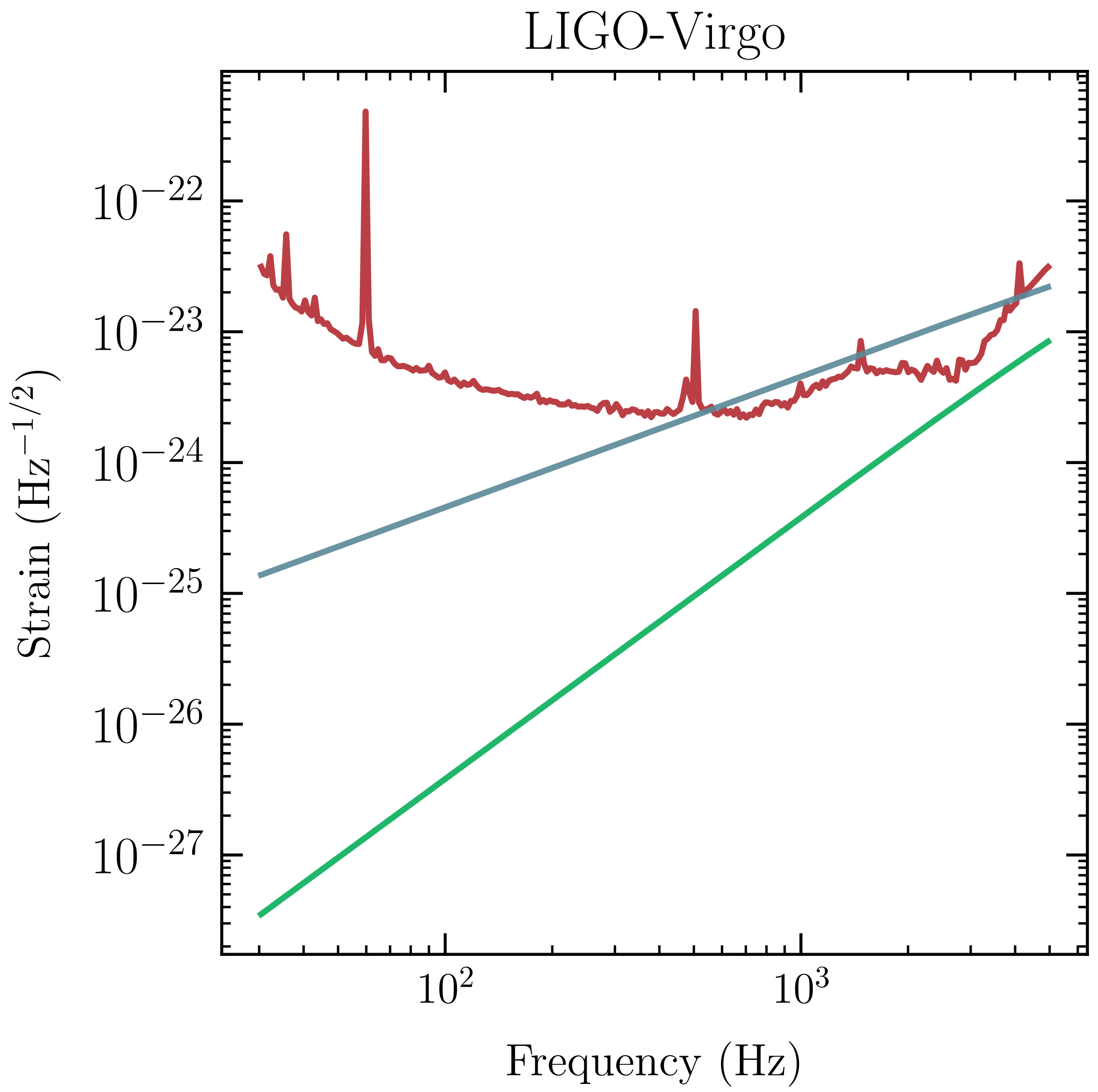
Equivalent Physical Descriptions

A model for pheno

- Distinctive Angular Correlations Predicted already in VZ1







- Consistent with LIGO and Holometer data

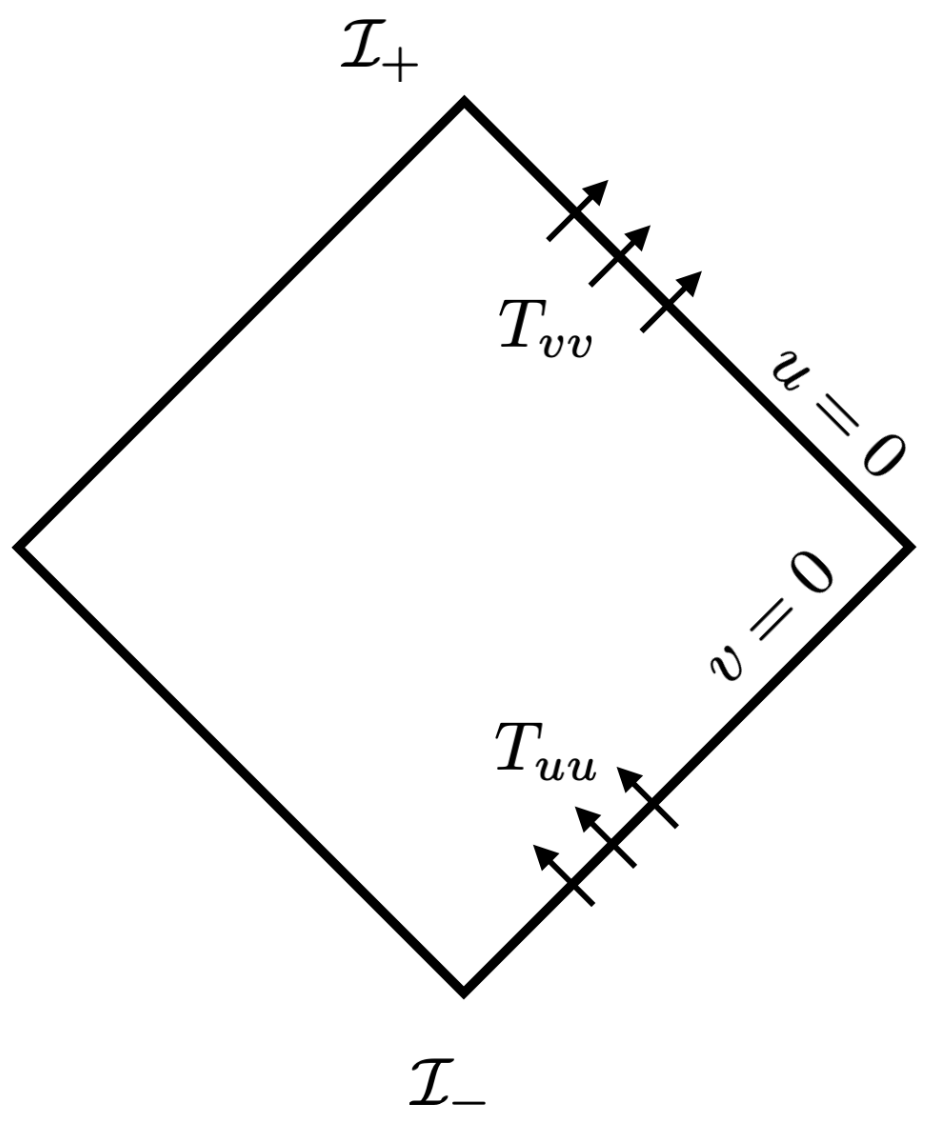
Li, Lee, Chen, KZ 2209.07543

What are we testing?

Fundamental Uncertainty in Light Ray Operators...

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

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



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

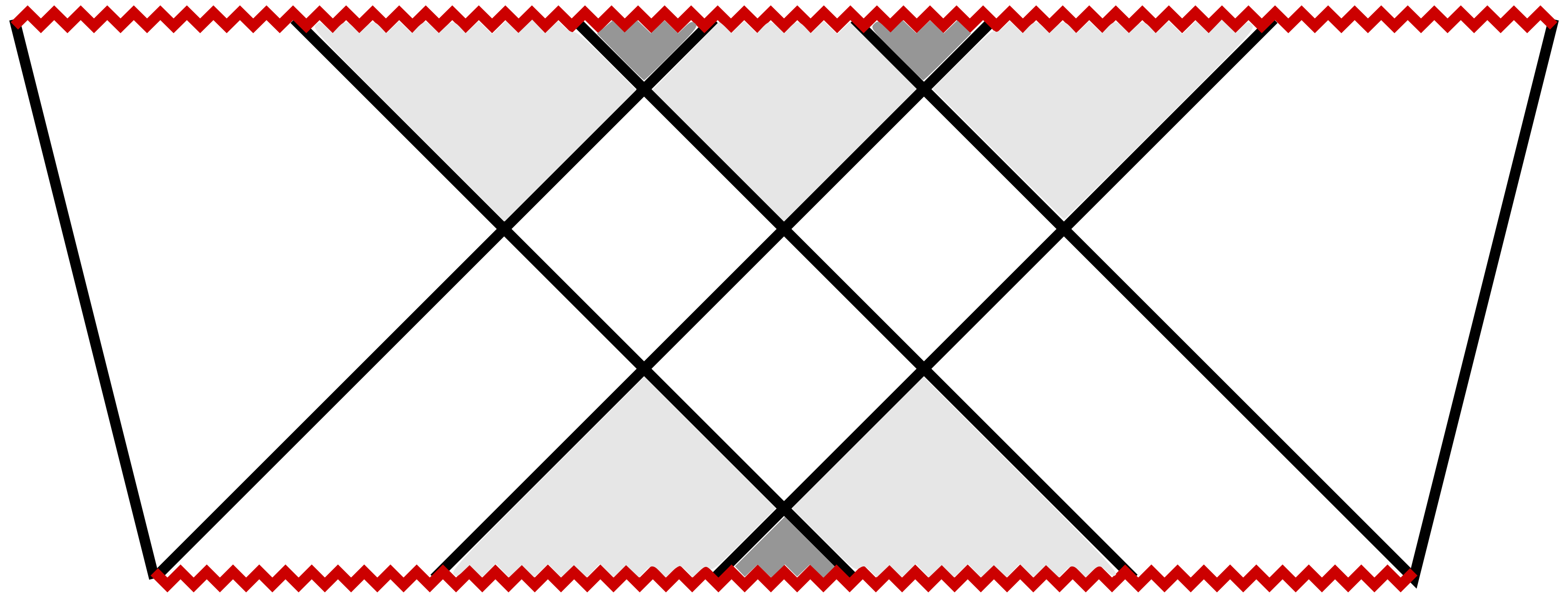
$$X^u(u,\Omega) = L - u + \delta u(u,\Omega)$$

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

Verlinde, KZ 2208.01059

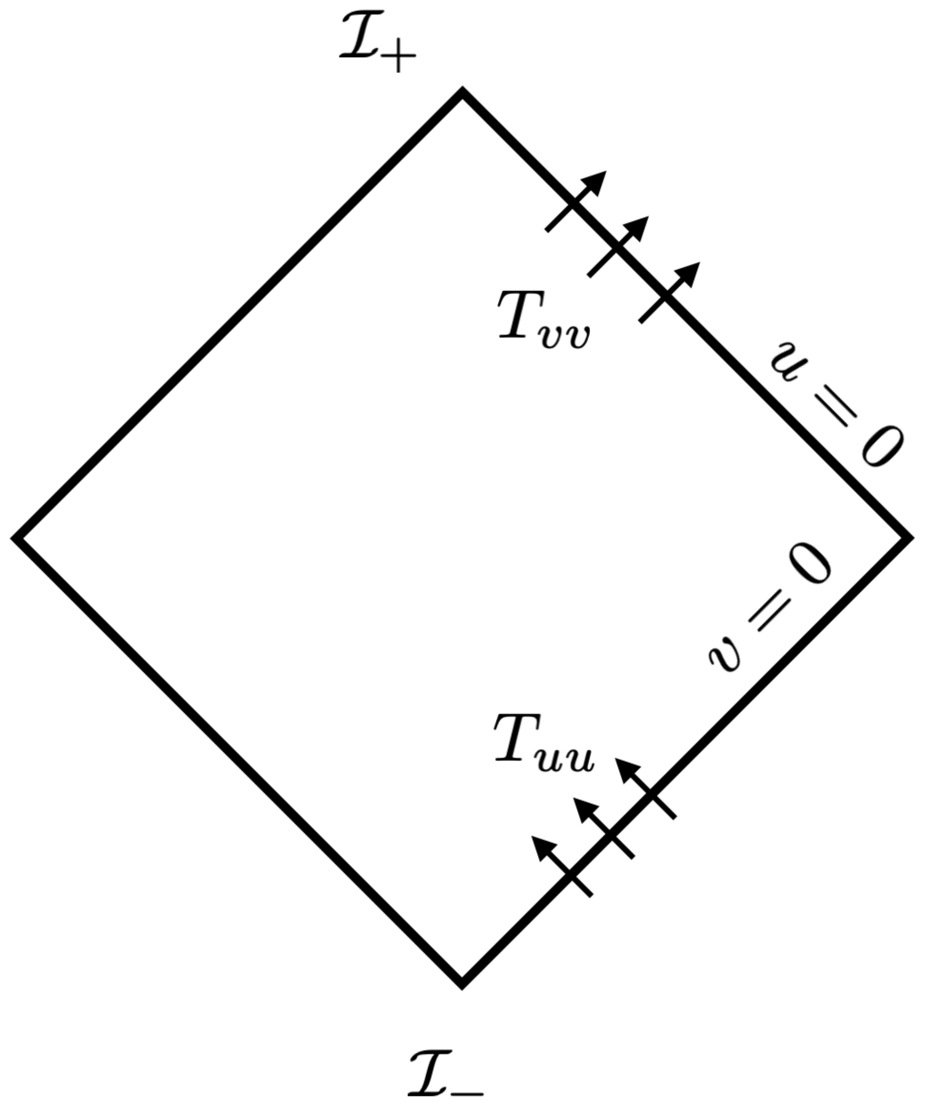
What are we testing?

Fundamental Uncertainty in Light Ray Operators...



Multiple shocks

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



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

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

Verlinde, KZ 2208.01059

The QuRIOS Collaboration

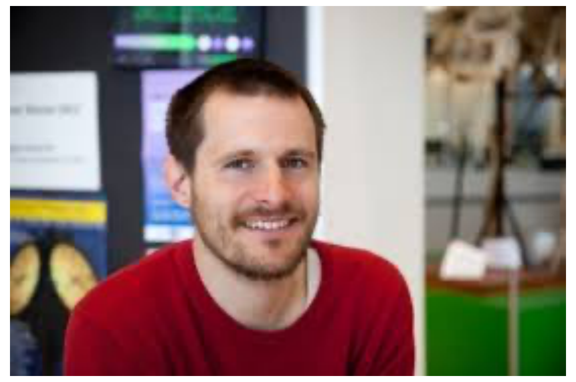
Quantum Gravity and Its Observational Signatures

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

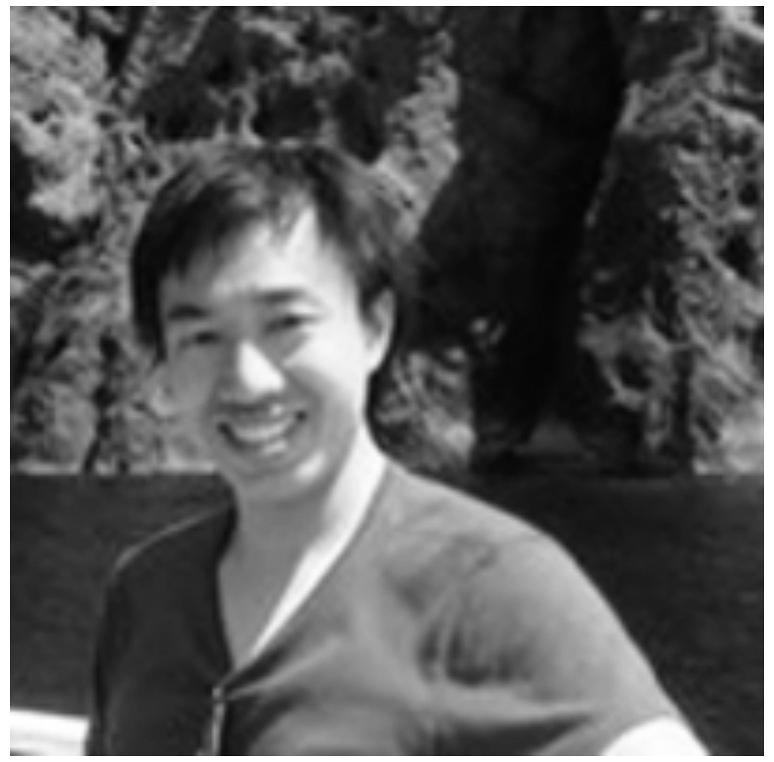
UCSB

HEISING-SIMONS FOUNDATION

Heising Simons Fellows

Inaugural Group

Lars Aalsma



Temple He

Ana-Maria Raclariu

Claire Zukowski

Allic Sivaramakrishnan

Kwinten Fransen

Dominik Neuenfeld

Local Theory Effort

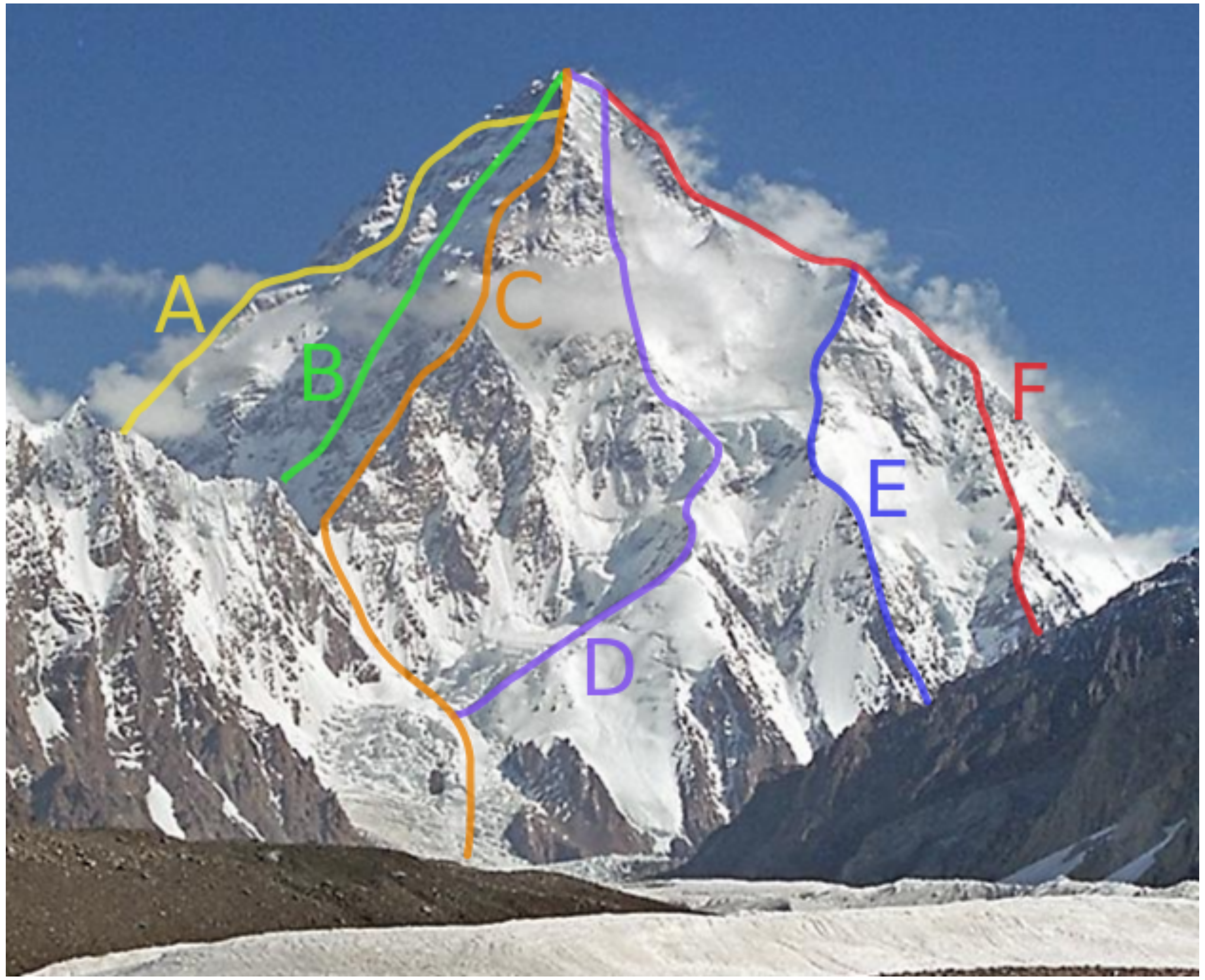
On QuRIOS & GQuEST

One Mountain, Many Faces

Equivalent physical descriptions

w/He,Sivaramakrishnan,Wilson

G. Length Operator



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