Measurement of Quantum Fluctuations in Geometry

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Can we measure quantum behavior of spacetime geometry?
Holographic Quantum Geometry

- Spacetime is a quantum system
- Standard field quantization in classical spacetime creates "spacetime foam" at Planck length,

\[ l_P = \sqrt{\frac{\hbar G_N}{c^3}} = 1.616 \times 10^{-33} \text{cm} \]

- Conjecture: the world is a holographic image formed by Planck wavelength fields
- Leads to transverse quantum fluctuations in geometry much larger than Planck limit- and measurable
How does quantum geometry affect quantum fields?

- Standard quantum field theory: geometry is classical, fields are quantized, modes are independent, "all physics is local"
- Appears to be a self-consistent approximation
- But in reality the whole world is a connected quantum system
- In holographic quantum geometry QFT breaks down: states and correlations are spatially nonlocal
- Current "evidence" for this is just theoretical
- New analysis based on a simple holographic conjecture: spacetime positions are defined only to the limit of imaging with Planck wavelength radiation
- Predicts detectable fluctuations
Direct measurement of quantum geometry fluctuations

- Traditional experimental approach to small lengths/large energies is the high energy frontier-- accelerators
- For quantum geometry: position measurements by interferometers designed for gravitational wave detection (narrow wavefunction of macroscopic mass position)
- "holographic geometry" defined by 2D encoding of spacetime paths and events using Planck wavelength radiation
- Predicts a detectable effect: "holographic noise"
- black hole evaporation physics--- in the lab
- Spectrum and distinctive spatial character of the noise is predicted with no parameters
- An experimental program is motivated
“This is what we found out about Nature’s book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size.”

-Gerard ‘t Hooft

Everything about the 3D world can be encoded on a 2D surface at Planck resolution (?)
Holographic Quantum Geometry: theory

- Black holes: entropy = area/4 \[ S = \frac{A}{l_P^2} 4 \ln 2 \]
- Black hole evaporation
- Einstein's equations from heat flow
- Classical GR from surface theory
- Universal covariant entropy bound
- Exact state counts of extremal holes in large D
- AdS/CFT type dualities: N-1 dimensional duals

All suggest that quantum geometry lives on 2+1 dimensional null surfaces

Beckenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Padmanabhan
Holography 1: Black Hole Thermodynamics

- Beckenstein, Bardeen et al. (~1972): laws of black hole thermodynamics
- Area of event horizon, like entropy, always increases
- Entropy is identified with 1/4 of event horizon area in Planck units (not volume)
- Is there a deep reason connected with microscopic degrees of freedom of spacetime encoded on the surface?
Holography 2: Black Hole Evaporation

- Hawking (1975): black holes radiate ~thermal radiation, lose energy and disappear
- Is information lost? Or is quantum unitarity preserved?
- Degrees of freedom: evaporated quanta carry degrees of freedom (~1 per particle) as area decreases
- Black hole entropy may completely account for information of evaporated states, also assembly histories
- Is black hole completely described by information on 2+1D event horizon?
- Information of evaporated particles=entropy of hole
Holography 3: nearly-flat spacetime

- Unruh (1976): Hawking radiation seen by accelerating observer
- Appears with any event horizon, not just black holes: identify entropy of thermal radiation with missing information
- Jacobson (1995): Einstein equation derived from thermodynamics (~ equation of state)
- Classical GR from 2+1D null surface  (Padmanabhan 2007)
Holography 4: Covariant (Holographic) Entropy Bounds

- 't Hooft (1985): black holes are quantum systems
- 't Hooft, Susskind et al. (~1993): world is "holographic", encoded in 2+1D at the Planck scale
- Black hole is highest entropy state (per volume) and sets bound on entropy of any system (includes quantum degrees of freedom of spacetime)
- All physics within a 3D volume can be encoded on a 2D bounding surface ("holographic principle")
- Bousso (2002): holographic principle generalized to "covariant entropy bound" based on causal diamonds: entropy of 3D light sheets bounded by area of 2D bounding surface in Planck units
- Suggests that 3+1D geometry emerges from a quantum theory in 2+1D: light sheets
3+1D spacetime emerging from 2+1D: null surface from 2D surface element
Holography 5: hints from string/M theory

- Strominger, Vafa (1996): count degrees of freedom of extremal higher-dimension black holes using duality
- All degrees of freedom appear accounted for
- Agrees with Hawking/Beckenstein thermodynamic count
- Unitary quantum system (but zero temperature)
- Strong indication of a minimum length ~ Planck length
- What do the degrees of freedom look like in a realistic system?
Holography 6: Exact dual theories in N-1 dimensions

- Maldacena, Witten et al. (1997…): AdS/CFT correspondence
- N dimensional conformal field "boundary" theory exactly maps onto (is dual to) N+1 dimensional "bulk" theory with gravity and supersymmetric field theory
- Alishahiha et al.: de Sitter spacetime in N dimensions maps onto de Sitter in N+1, N-1
- Is nearly flat 3+1 spacetime described as a dual in 2+1?
Holographic quantum geometry implements covariant (holographic) entropy bound in emergent 3+1D spacetime

- Reflects Hilbert space of 2+1D theory
- By construction, follows light sheets of covariant Bousso formulation
- Far fewer independent modes than field theory quantized in 3+1D
- Independent pixels in 3D volume = 1/4 area of 2D null surface element
A holographic world is blurry

*limited information content*

What does it look like "from inside"?
Holographic Quantum Geometry

- Spacetime is a quantum system
- **Conjecture:** the world is a holographic image formed by Planck wavelength fields
- "from inside": transverse quantum fluctuations in position much larger than Planck length

\[ l_P = \sqrt{\frac{\hbar G_N}{c^3}} = 1.616 \times 10^{-33} \text{cm} \]
Ray limit of wave optics: Rayleigh uncertainty

- Aperture $D$, wavelength $\lambda$ : angular resolution $\lambda/D$
- Size of diffraction spot at distance $L$: $L\lambda/D$
- Endpoints of a ray can be anywhere in aperture, spot path is determined imprecisely by waves
- Minimum uncertainty at given $L$ when aperture size = spot size, or

$$D = \sqrt{\lambda L}$$
The case of a real hologram

- For optical light and a distance of about a meter,\[ D = \sqrt{\lambda L} \]
is about a millimeter

- This is why even perfect holograms look blurry

- If you "lived inside" a hologram, you could tell by measuring the blurring
Indeterminacy of a Planckian path: rays seen by a "Planck wavelength telescope"

- Spacetime metric defined by paths between events
- Events on worldline = quantum interactions with Planck wavelength radiation
- Transverse localization creates indeterminacy in conjugate transverse momentum, angular orientation
- ~Indeterminacy of worldlines in classical geometry
\[ \Delta(\text{measured position}) \times \Delta(\text{momentum of perturbation}) > \hbar/2 \]
Heisenberg Microscope

- Measures transverse position by imaging using scattered light.
- Complementarity between measured position, transverse photon momentum.
- Observables do not have independent classical meaning.
"Planck telescope"

- Focus Heisenberg microscope very far away
- Set minimum wavelength≈ Planck scale
- Minimum uncertainty in angle or transverse position when size of aperture ~ size of its own diffraction spot
- corresponds to encoding scale of holographic image at the same distance
- Conjecture that holographic Planck image is all there is to know about distant position
Uncertainty: Heisenberg and Holographic

- "Heisenberg microscope": transverse position of a remote body measured by angular position~ detected position of radiation particle in image
- Fixed 3D classical space
- $\Delta(\text{measured transverse position of a body}) \times \Delta(\text{momentum of measuring radiation}) > \hbar/2$
- $\Delta$ independent of microscope aperture, focal length
- Property of body, radiation
- State of body, radiation depends on measurement

- "Planck telescope": transverse position of remote events measured by Planck radiation
- Observables (including positions) encoded in 2D apertures with Planck waves
- $\Delta(\text{position 1}) \times \Delta(\text{position 2}) > (\text{Planck length}) \times (\text{separation}/2)$
- $\Delta$ position ~ optimal "aperture", depends on separation
- Property of (quantum) spacetime geometry: \textit{limiting precision of Planck imaging}
- State of metric depends on measurement
Angles are indeterminate at the Planck scale, and become better defined at larger separations:

\[ \Delta \theta(L) = \left( \frac{l_P}{L} \right)^{1/2} \]

But uncertainty in relative transverse position increases at larger separations:

\[ \Delta x_{\perp}^2 > l_P L \]

- Not the usual classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales
Angular orientation of a null path defined by Planck wavelength particles is uncertain, with standard deviation

\[ \Delta \theta(L) = \left( \frac{l_P}{L} \right)^{1/2} \]
Holographic indeterminacy of distant spacetime allows black hole evaporation to be a reversible, information-preserving quantum process.

- One degree of freedom leaves the hole for each evaporated particle, wavelengths of order hole size.

- If the quantum states of the evaporated particles allowed transverse position observables with 3D Planck precision, at large distance they would contain more information than the hole.

- With holographic indeterminacy of distant spacetime, distant positions are not all distinguishable states and the problem disappears.
Holographic Uncertainty in position

Positions transverse to a null trajectory at separation $L$ have standard deviations:

$$\Delta x_1 \Delta x_2 > \frac{l_P L}{2}$$

For macroscopic $L$ the uncertainty is much larger than the Planck length, and is measurable.

Measuring fluctuations in quantum geometry

- Distant spacetime is only defined insofar as it can be measured locally using Planck radiation
- Distant events are fuzzy objects, not points
- Endpoints of trajectories (interaction events) are uncertain
- Indeterminacy of worldlines leads to fluctuations in measured quantities
What is the best microscope for measuring quantum geometry?

CERN/FNAL: $\text{TeV}^{-1} \approx 10^{-18} \text{ m}$

LIGO/GEO: $\approx 10^{-19} \text{ m}$ over $\approx 10^3 \text{ m baseline}$
Interferometers as Planck telescopes

- Nonlocality: precise relative positions at km scales
- Fractional precision: angle < $10^{-20}$, > "halfway to Planck"
- Transverse position measured in some configurations
- Proof masses have narrow position wavefunction, measure spacetime wavefunction
- Detect holographic blurring: noise in signal stream
Normal incidence optics: phase signal does not record the transverse position of a surface

- But phase of beam-split signal is sensitive to transverse position of surface
Measurement of transverse position at beamsplitter

- Phase signal measures difference of paths, position of beamsplitter
- Quantum state is prepared along one axis, measured along another
- Measurement collapses position state into a definite classical metric
- Phase difference accumulates uncertainty in quadrature: ~Planck length per Planck time
Measurement of transverse position of beamsplitter

- Wavefront from z direction defines a null surface $N$
- Positions of reflection events have transverse uncertainty

\[ \Delta x_1 \Delta x_2 > l_P L / 2 \]

- Independent samplings from different null surfaces accumulate signal phase uncertainty

\[ \Delta^2 (x_1 - x_2) > c^2 t_z t_P \]
Another view: transverse Planck random walk

- A null sheet executes a random walk transverse to its direction of propagation, a Planck length per Planck time
Effect of beamsplitter position uncertainty on signal

inclined wavefronts separated by time $t$ arrive with
standard deviation from reference wavefronts

$$\Delta t = \sqrt{t_P t \sin \theta \sin 2\theta}$$

adds the same noise to interferometer signal as a
random walk of beamsplitter position

$$\langle \Delta l^2 \rangle_H > c t l_P \sin \theta (\sin 2\theta)^2$$

this is a new effect predicted with no parameters
Power Spectral Density of Fluctuations

Uncertainty in angle $\sim$ dimensionless metric perturbation

$$\Delta \theta(L) = (l_P/L)^{1/2}$$

$\sim$ metric fluctuations with flat power spectral density

$$h^2_H \sim L \Delta \theta^2 \approx t_P$$

$h^2_H$ = mean square perturbation per frequency interval

(prediction with no parameters, Planck length is the only scale)
Holographic Noise

Universal **holographic noise** \( \sim \) flat power spectral density of metric **shear** perturbations:

\[
h \approx \sqrt{t_P} \approx 2.3 \times 10^{-22} \text{Hz}^{-1/2}
\]

- A property of holographic quantum geometry
- Prediction of spectrum with no parameters
- Prediction of spatial shear character: only detectable in systems comparing position observables in orthogonal directions
Holographic fluctuations do not carry energy or information

- classical gauge mode
- sampling noise rather than thermal noise
- Necessary so the number of distinguishable positions does not exceed holographic bound on Hilbert space dimension
- No curvature
- no strain, just shear
- no detectable effect in a purely radial measurement
LIGO Hanford Observatory
Schematic layout of LIGO

Fig. 1. Schematic layout of a LIGO interferometer.
vibration-isolated platform

initial alignment

test mass suspended on fine wire
UW Physics undergrads at LIGO Hanford Observatory
LIGO noise (astro-ph/0608606)

Measured LIGO noise spectrum (GW strain equivalent, rms power spectral density)

$\sqrt{t_P} = 2.3 \times 10^{-22} / \sqrt{\text{Hz}}$

(if shear=strain)

holographic noise spectrum (shear)

Measured LIGO noise spectrum (GW strain equivalent, rms power spectral density)
Why doesn't LIGO detect holographic noise?

- EITHER holographic noise does not exist, OR:
- LIGO layout is not sensitive to transverse displacement noise (relationship of holographic to gravitational wave depends on details of the system layout)

Fig. 1. Schematic layout of a LIGO interferometer.

Transverse position measurement is not made in FP cavities
LIGO S5 run: noise in displacement units

- Allow for lack of holographic noise from FP arm cavities
- In displacement units, estimated holographic noise is below sensitivity of last science run
- May be detectable with enhanced/advanced LIGO

Rough but zero-parameter estimate of holographic noise in LIGO (displacement units)
GEO-600 (Hannover)
Large power cycles through beamsplitter, adds transverse holographic noise.
Noise in GEO600

Rough but zero-parameter estimate of holographic noise in GEO600 (equivalent strain)

H. Lück, S. Hild, K. Danzmann, K. Strain

CJH: arXiv:0712.3419
"Mystery Noise" in GEO600

Rough but zero-parameter estimate of holographic noise in GEO600 (equivalent strain)

H. Lück, S. Hild, K. Danzmann

CJH: arXiv:0712.3419
Beamsplitter inserts holographic uncertainty into signal

system with LIGO, GEO600 technology can detect holographic fluctuations of the metric if they exist

Signatures: spectrum, spatial shear

Interferometers can detect quantum fluctuations of geometry

CJH: arXiv:0712.3419
New interferometers: beyond GW detectors

• Spectrum: 100 to 1000 Hz with existing apparatus

• Higher $f$ with larger laser power (above GW sources); resonant cavity limit possible

• Test specific geometry dependence (shear character, variation with angle) with different configurations

• Needs are different from GW studies

• But requires similar technologies
What we might learn from holographic noise experiments

- Measurement of quantum behavior of spacetime: holographic geometry, spectrum and spatial character of fluctuations
- Quantum weirdness: detectable nonlocal effects of observational measurement choices on spacetime metric
- Establish quantum geometry framework for complete fundamental theory (2+1D null projection, etc.)
- Clues to nature of vacuum fluctuations, quantum physics of Dark Energy
- Or, maybe nothing!?