How does space-time work?

Craig Hogan
University of Chicago and Fermilab

Quantum systems, entanglement, and correlations

Whole quantum system = superposition of states
Every subsystem of a whole is entangled with every other
A measurement of one subsystem affects the state of others
The observer is also part of the system
Theory only predicts correlations among observables
Specific outcomes are “indeterminate”
Nothing happens at a definite place or time: no “locality”
(“spooky” outcomes still obey causality: no magic signals)

entangled subsystems: cat and poison

\[ \frac{1}{\sqrt{2}} |\text{cat}\rangle + \frac{1}{\sqrt{2}} |\text{poison}\rangle \]
Classical space-time and quantum matter

Classical space-time is continuous, observer independent, deterministic, and based on locally defined quantities.

It couples to quantum mass-energy with quantized action, observer-dependent states, indeterminacy, and nonlocality.

Nobody knows how this works.

Maybe space-time emerges from a quantum system at a deeper level.

- Deep degrees of freedom are not fields, particles or waves.
- Gravity = excited states of those deep degrees of freedom.
- Space-time positional relationships are quantum observables.

*Correlations of quantum geometry might be accessible to real experiments.*
Quantum gravity happens at the Planck scale

Planck length: \( \left( \frac{\hbar G}{c^3} \right)^{1/2} = 1.6 \times 10^{-35} \) metres,

Planck mass: \( \left( \frac{\hbar c}{G} \right)^{1/2} = 2.1 \times 10^{-8} \) kilograms,

Planck time: \( \left( \frac{\hbar G}{c^5} \right)^{1/2} = 5.4 \times 10^{-44} \) seconds,

Planck energy: \( \left( \frac{\hbar c^5}{G} \right)^{1/2} = 1.2 \times 10^{19} \) GeV.

\( \hbar \) reduced Planck constant from quantum mechanics

\( c \) speed of light from special relativity

\( G \) gravitational constant from general relativity
At the Planck length, single quanta = black holes

*Smaller lengths are impossible*

What happens to the “local” inertial frame?

\[ \lambda = \frac{\hbar c}{E} \]

\[ R = \frac{2GM}{c^2} \]

Planck length \( \sim 10^{-35} \) meters

\[ l_P \equiv ct_P \equiv \sqrt{\frac{\hbar G}{c^3}} \]
Rotation and direction are not defined at the Planck length

Quantum

log (size)

Black Hole

log (mass-energy)

Single quantum drags frame like a maximally rotating black hole
Rotation in classical space

Space is a physical entity with measurable effects.

Newton’s proof of “absolute” space: centrifugal effect in a rotating vessel of water.

Also measurable with atoms, interferometers, etc.
Newton’s idea survives in general relativity and quantum theory: the “local inertial frame”

Rotation is locally defined and measurable

Spins of quantum particles are measured relative to the local inertial frame

Inertial frame is defined to infinitesimal scales
Absolute space in general relativity

Space still defines an absolute local inertial frame
A new effect in GR: “Frame dragging” or “Lense-Thirring”
  local inertial frame is “dragged” by dynamical space-time
  local frame rotates relative to the distant universe
Drag is measured in the solar system
It becomes extreme near black holes

Apache Point Observatory lunar laser ranging
Gravity Probe-B
Indeterminacy of the inertial frame

A quantum measuring device drags space
Indeterminate spin drags the inertial frame
The inertial frame is a quantum superposition
“Local” inertial frame is a statistical property that emerges on scales >> the Planck length

Rotation is “not a thing” at the Planck scale

Same goes for space, time, and directions: they all emerge only statistically, in larger systems

Planck scale degrees of freedom produce Planck scale deviations from classical trajectories

Symmetries of space-time on larger scales are shaped by correlations of Planck scale systems
Information and correlations

**Correlation <=> limited information**

Entropy of black hole event horizons: geometrical information is holographic

\[ \sim 1 \text{ bit per Planck area of causal diamond} \]

Less information than volume scaling expected for independent Planck scale systems

Holographic information implies exotic nonlocal correlations (lack of independence) on all scales

(even if nothing “moves” farther than a Planck length and no correlation lasts longer than a Planck time)
“MR diagram” of everything

Planck scale inconsistency

most compact classical geometry (black hole, $M=R/2$) (General Relativity)

most compact quantum system (particle, $m=1/L$) (Quantum Field Theory)
Quantum geometry adds exotic correlations on macroscopic scales.
Exotic large scale correlations

Even flat space-time is “made of” Planck scale quanta

Quantum geometry ~ Planck length displacements

Those displacements are nonlocally correlated on scales much larger than the Planck length

Normalization is fixed by holographic gravity

Correlation is constrained by Lorentz invariance

~ rotational fluctuations in the inertial frame
Lorentz invariant exotic rotational correlations

- Information density = Planck bandwidth in proper time on a measurement world line
  (displacements correlated within a Planck time)

- Transverse spacelike displacements on light cones
  (Planck length displacement everywhere on light cones)

http://arxiv.org/abs/1509.07997
https://arxiv.org/abs/1607.03048
Light-cone foliation of space-time

Spacelike displacements ~ Planck length, timelike correlations localized within ~ Planck time
A way to visualize exotic correlations

All of space twists randomly back and forth

The only thing that does not “move” is the observer

The motion is not really motion, but quantum noise in the differentiation of space and time

All “motions” are ~ Planck length

Directions on all scales fluctuate on a light crossing time

The rotation rate diminishes in a long time/large volume average
Exotic rotational correlations on spacelike surfaces

Mean rotation vanishes, mean square does not

Rotational fluctuation diminishes at large $R$:

$$\langle \Delta \theta^2 \rangle_R \approx \langle \hat{x}_\perp^2 \rangle_R / R^2 = \ell_P / R$$

$$\langle \omega^2 (R) \rangle \approx c^2 \ell_P R^{-3}$$
Exotic correlations have real physical effects

Everything rotationally fluctuates a little

Correlated displacements affect trajectories

Instead of Newton’s bucket (centrifugal acceleration), measure rotation with light

Transverse propagation gets an exotic displacement

No effect is observable locally: requires measurement of a closed path in space-time (e.g., interferometers)

The accumulated effect is much larger than a Planck length
Interferometers are now good enough to study exotic space-time correlations

Signal ~ difference of lengths of optical paths along two arms that begin and end at a beamsplitter

Response to exotic correlations (or lack thereof) probes the relationship between quantum fields and quantum geometry
An instrument that measures Planck scale correlations: the Fermilab Holometer

First results: PRL 117, 111102 (2016)
https://arxiv.org/abs/1703.08503
https://arxiv.org/abs/1611.08265
https://arxiv.org/abs/1611.05560
final shear constraints
instrument design
gravitational wave bounds
Planck sensitivity to correlations

**Fluctuation noise power spectral density of fractional length distortions:**

\[
h^2(f, t) \equiv \int_{-\infty}^{\infty} \left( \frac{\delta L(t)}{L} \frac{\delta L(t - \tau)}{L} \right) e^{-2\pi i \tau f} d\tau
\]

To reveal exotic correlations, this quantity must be measured with a precision smaller than the Planck time.

For a measurement limited by quantum photon noise, sensitivity \( \sim \frac{\text{laser period}}{\text{number of photons}} \)

Planck sensitivity is achieved with \( \sim 10^{29} \) photons
Holometer design principles

Similar to LIGO and GEO-600:

- power-recycled Michelson interferometers
- positions of mirrors measured to $\sim 10^{-18}$ m

But with some differences:

- **fast signal sampling and correlation to match bandwidth of predicted noise spectrum (spacelike -> “superluminal”)**
- correlate two separate nearby interferometers to separate geometry from environmental and standard quantum noise

Modest size for simplicity and affordability
East arms of original vacuum system configuration
Ben Brubaker bolting the holometer vacuum system together
Vacuum compatible optics mounts

- In-vacuum mounts are actuated by UHV picomotors
- Seismic isolation stage
- Power-recycling mirror
- Beamsplitter
The Holometer in High-Power Operation

Interference beam-images (The science signals)
Real, Planck precision data!

Dual-interferometer cross-spectral density (CSD):
  Integrated over 704 hours
  Binned at 250 kHz frequency resolution

Each data point is a statistically independent measurement
Shear correlations: departures from classical space-time are constrained to be far below a Planck length.

Constrains a symmetry of quantum gravitational degrees of freedom.

Proves the viability of the measurement technique.

No constraint on rotational correlations.
Exotic rotational correlations will be measured with reconfigured Holometer

Signal is predicted by Lorentz invariant model

One parameter = Planck length, determined by gravity

Holometer is now reconfigured for rotational response

It should have enough sensitivity to measure the predicted signal
New experimental layout is sensitive to rotational fluctuations

Bends the east arms 90° at their midpoint

Light no longer propagates purely radially relative to the beamsplitter
New layout: bend arm to measure rotational fluctuations
“Spooky” entanglement of causal diamonds: nearby interferometers see correlated rotational fluctuations leads to cross correlations of signals in separate but nearby interferometers
Reconfigured vacuum system
Predicted signal in reconfiguration

Model of signal response predicts detectable spectrum of exotic noise with Planck normalization

\[ C_{SS}(f | l_P) \, (m^2/Hz) \]

Michelson with one bent arm

\[ l_P \equiv \sqrt{\hbar G/c^3} = 1.616 \times 10^{-35} m \]

\[ L = 19.5 m \]

arXiv:1607.03048
The Holometer Collaboration

**University of Chicago**
Craig Hogan (Proj. Scientist)
Ohkyung Kwon*
Bobby Lanza*
Lee McCuller*
Stephan Meyer (co-PI)
Jonathan Richardson*

**Fermi National Accelerator Laboratory**
Aaron Chou (co-PI)
Henry Glass
Chris Stoughton
Ray Tomlin

**Massachusetts Institute of Technology**
Rainer Weiss

**University of Michigan**
Richard Gustafson

**Vanderbilt University**
Brittany Kamai*

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Summary

Planck scale rotational quantum fluctuations in the inertial frame could be observable

A Lorentz invariant model of Planck scale rotational degrees of freedom predicts statistical properties of interferometer signals

It will be tested with the reconfigured Holometer

Oh, and one more thing: Rotational fluctuations might account for the observed cosmological constant—
Cosmic acceleration is supported by a wealth of precise data.
Cosmological constant created by rotationally fluctuating geometry

Cosmological constant ~ “dark energy” of the vacuum

Field theory vastly overestimates the dark energy density of the quantum field vacuum

We need to explain both why it is so small, and why it is not exactly zero
Why is the cosmological constant so small?

In emergent model, flat space-time is the ground state with no matter fields

Causal structure is an exact symmetry of the ground state: null intervals are not changed by excitations

Light cones extend to spacelike infinity

Approximate symmetry in quantum gravity: small excitations preserve nearly zero curvature on all scales
Why is the cosmological constant not exactly zero?

Actual quantum gravity includes fields as well as geometry.

Field vacua slightly change causal structure.

Geometrical correlations entangle with these states.

Breaks the scale invariance of gravity.
Compute the value of the cosmological constant

Equate cosmic information flow with information of field vacuum

Entropy of cosmic horizon: \[ S = \pi t_P^{-2} H_\Lambda^{-2} \quad H_\Lambda^2 \equiv \Lambda/3 \]

Cosmic data give: \[ H_\Lambda = \Omega_{\Lambda}^{1/2} H_0 = 0.99 \pm 0.018 \times 10^{-61} t_P^{-1} \]

cosmic information matches field information with a cutoff at
\[ k_\Lambda \equiv \left( H_\Lambda 9\pi^2/2 \right)^{1/3} \]
\[ k_\Lambda c \hbar = 1.65 \pm 0.01 \times 10^{-20} m_P c^2 = 201 \pm 1.2 \text{ MeV} \]

Cosmic information closely matches the strong interactions

Similar to coincidences known to e.g. Dirac, Eddington, Zeldovich, Bjorken:

\[ m^3_{\text{pion}} \sim H_0 \quad \text{in Planck units} \]
Centrifugal interpretation of cosmic acceleration

Classical centrifugal acceleration at distance \( r \) from an axis of rotation:

\[
\ddot{r} = \omega^2 r
\]

Cosmic acceleration by cosmological constant at separation \( r \) :

\[
\ddot{r} = H^2 \Lambda r
\]

Mean square exotic rotational fluctuation:

\[
\langle \omega^2(R) \rangle \approx c^2 l_P R^{-3}
\]

Match exotic and cosmic acceleration:

\[
\langle \omega(R_\Lambda)^2 \rangle = H^2_\Lambda
\]

in volume of size: \( R_\Lambda/l_P \approx (H_\Lambda t_P)^{-2/3} \)

\(~ \text{scale where information flows between fields and geometry}~\)

Twists of the strong interaction vacuum "shake space apart" at larger length scales
Cosmological constant is not exactly constant: it fluctuates macroscopically in space and time

\[ \frac{R_\Lambda}{l_P} \approx (H_\Lambda t_P)^{-2/3} \]

Centrifugal acceleration from rotational fluctuations matches cosmic acceleration on this scale \( \sim 60 \text{ km} \), the Chandrasekhar radius for \( m_Q \sim 200 \text{ MeV} \)

On smaller scales, exotic rotational fluctuations are virtual— they have no effect on the emergent metric

On larger scales, they act like real rotational fluctuations

fluctuates by \( \sim 1 \text{ Fermi} \) at \( \sim 5000 \text{ Hz} \), with \( \sim 60 \text{ km} \) coherence

cosmic acceleration/radial time dilation fluctuates on this scale

Fluctuations are unobservable with current techniques
In this scenario, the cosmological constant is determined by known scales of physics: Planck and Fermi (gravity and QCD)

The very long cosmic timescale comes from a similar combination of constants to those that determine a stellar lifetime

For different physical reasons, they both depend on the same power of the large dimensionless ratio,

\[
\text{Planck mass/ proton mass}
\]

In unified field theory, this large number is explained by the logarithmic running of coupling constants

Numerically it is the same coincidence noticed by Dirac
Main points of this talk

Physical effects of quantum geometry at the Planck scale are not confined to the Planck scale, or to extreme environments like inflation or black holes.

Quantum geometry should produce exotic rotational correlations on all scales, even in flat space-time.

They *might* be easier to understand from basic principles than the full dynamical theory of quantum gravity.

They *might* be accessible to direct experimental measurement.

They *might* help to explain cosmic acceleration.
Quantum gravity and QCD could explain the cosmological constant.
Recent papers

• Instrument paper:
  • The Holometer: an instrument to probe Planckian quantum geometry 2017 *Classical and Quantum Gravity* **34** 065005

• Experimental results:
  • First measurements of high frequency cross-spectra from a pair of large Michelson interferometers 2016 *Phys. Rev. Lett.* **117** 111102
  • MHz gravitational wave constraints with decameter Michelson interferometers 2017, *Phys. Rev.* D **95**, 063002
  • Interferometric constraints on quantum geometrical shear noise correlations 2017 *Classical and Quantum Gravity* **34** 165005

• Theory:
  • Interferometric tests of Planckian quantum geometry models 2016 *Classical and Quantum Gravity* **33** 105004
  • Statistical measures of Planck scale signal correlations in interferometers *Classical and Quantum Gravity* 2017 **34** 075006
  • Statistical model of exotic rotational correlations in emergent space-time 2017 *Classical and Quantum Gravity* **34** 135006
  • Exotic rotational correlations in quantum geometry, 2017 *Phys. Rev. D* **95** 104050