A History of Reality:

The Road to Ontology, the Pursuits of Determinism and Causality, and the Limits of Empirical Epistemology

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KAIST • Fermilab Holometer Collaboration

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A History of Reality: The Road to Ontology, the Pursuits of Determinism and Causality, and the Limits of Empirical Epistemology

How do we *know*?

$$F \quad = \; m\,a$$

A law of nature?

F = m a

How do we know this?

How do we *know*?

$$F(t) \; = \; m\,a(t)$$

Galileo: Physical motion can be described as a function of "time."

But can we know "time"? "Clocks" are built on *theories* of "time"!

F(t) = m a(t)

Galileo was the first to express physical motion as a function of time. He discovers that the oscillations of a pendulum "take equal time."

But how? There was no clock then! He used his pulse.

But soon thereafter, doctors started using pendulums to measure pulses. Every modern clock uses an oscillator to keep time.

This is a crisis of epistemology!

Time is an *untestable* mathematical axiom? What is *real*?

$$F(t) \; = \; m\,a(t)$$

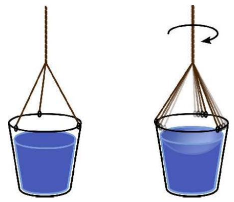
Newton: There is an unobservable time, "***absolute** and equal to itself*."

You can only measure things evolving through time, and not time itself?!

Newton avoids the issue with an untestable mathematical axiom: there is an unobservable time, absolute and equal to itself.

This is now a crisis of ontology: if you can only measure things evolving through time, and not time itself, is it real?

Space is *absolute*?



Newton: Local rotation agrees with measurements against distant stars.

There must be a universal global inertial frame of reference.

Newton further claims, space is absolute, too.

But if you and I were in empty space with no reference, we can only measure relational motion, right?

Newton's argument was that local rotation, measured by an observer with a spinning bucket of water, agrees with distant stars.

So there must be a universal global inertial frame of reference.

What is *nothingness*?

Enlightenment

Do we need a First Cause that "created" the universe—and time—from nothing?

If we only have some laws of the universe, and nothing else, is that nothing?

What can be defined as a physical ***reality***?

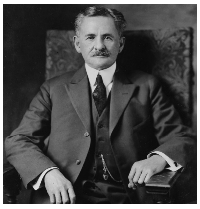
Newton's natural philosophy was widely read during the Enlightenment.

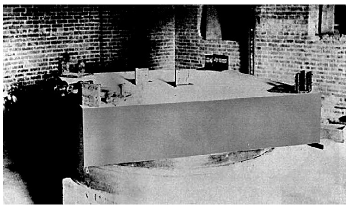
Humanity started to rigorously examine ideas like first cause, that "created" the universe from nothing.

But "creation" already assumes some notion of time, which must "exist" in some sense.

Also, what is the meaning of nothingness? If we only have some laws of the universe, and nothing else, is that nothing? What can be defined as a physical reality?

The most famous "failed" experiment in history: an inconsistency...





Michelson: The speed of light is independent of any observer frame in space-time.

There can be no background against which to measure it.

No "aether": no universal medium, no global refrence frame.

A couple of centuries later, Newton's framework runs into an inconsistency.

We thought that light traveled through a universal medium, called "aether," so an observer moving relative to it would see a different speed of light.

But Michelson shows that this global reference does not exist:

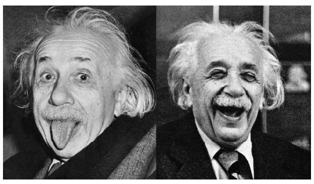
The speed of light is independent of any observer frame in space-time; there can be no background against which to measure it.

Maybe space-time is not absolute?

Relativity: a theory of absolute reality

Einstein insists on the ***principle of invariance***:

- There must be a consistent underlying physics, independent of an arbitrary choice of coordinate frame or measurements relative to a specific observer.
- Example: Regardless of which twin "stayed home" and which twin went on a space trip, we know consistently which one aged more in time.



General Relativity:

- The gravitational field is *space-time itself*. It must have a reality independent from the background space-time coordinates on which we construct all other theories of physics.
  - We can't use x, y, z, and t in equations anymore. But GR works elegantly!
  - GR is soon beautifully confirmed by experiments.

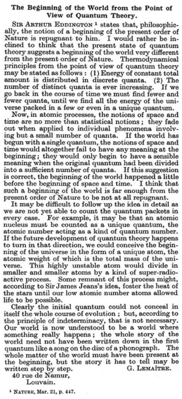
Einstein solves this inconsistency with relativity, which is, despite its name, actually a theory of absolute reality.

Relativity takes the Newtonian inconsistency, and insists on the principle of invariance:

There must be a consistent underlying physics that is independent of an arbitrary choice of coordinate frame, or measurements relative to a specific observer.

In particular, general relativity insists that the gravitational field is space-time itself, and therefore must have a reality independent from the background space-time coordinates on which we construct all other theories of physics.

The Big Bang, and the energy of "empty space"?



The Beginning of the World from the Point of View of Quantum Theory.

SIR ARTHUR EDDINGTON [1] states that, philosophically, the notion of a beginning of the present order of Nature is repugnant to him. I would rather be inclined to think that the present state of quantum theory suggests a beginning of the world very different from the present order of Nature. Thermodynamical principles from the point of view of quantum theory may be stated as follows: (1) Energy of constant total amount is distributed in discrete quanta. (2) The number of distinct quanta is ever increasing. If we go back in the course of time we must find fewer and fewer quanta, until we find all the energy of the universe packed in a few or even in a unique quantum.

Now, in atomic processes, the notions of space and time are no more than statistical notions; they fade out when applied to individual phenomena involving but a small number of quanta. If the world has begun with a single quantum, the notions of space and time would altogether fail to have any meaning at the beginning; they would only begin to have a sensible meaning when the original quantum had been divided into a sufficient number of quanta. If this suggestion is correct, the beginning of the world happened a little before the beginning of space and time. I think that such a beginning of the world is far enough from the present order of Nature to be not at all repugnant.

It may be difficult to follow up the idea in detail as we are not yet able to count the quantum packets in every case. For example, it may be that an atomic nucleus must be counted as a unique quantum, the atomic number acting as a kind of quantum number. If the future development of quantum theory happens to turn in that direction, we could conceive the beginning of the universe in the form of a unique atom, the atomic weight of which is the total mass of the universe. This highly unstable atom would divide in smaller and smaller atoms by a kind of super-radioactive process. Some remnant of this process might, according to Sir James Jeans's idea, foster the heat of the stars until our low atomic number atoms allowed life to be possible.

Clearly the initial quantum could not conceal in itself the whole course of evolution; but, according to the principle of indeterminacy, that is not necessary. Our world is now understood to be a world where something really happens; the whole story of the world need not have been written down in the first quantum like a song on the disc of a phonograph. The whole matter of the world must have been present at the beginning, but the story it has to tell may be written step by step.

G. LEMAÎTRE.

40 rue de Namur,
Louvain.

[1] NATURE, Mar. 21, p. 447.

Lemaître, a Catholic priest:

- GR describes an expanding universe.
- *Space-time itself had a "beginning"!*

Einstein adds a constant to "fix" GR.

Hubble's data confirms the expansion.

Einstein abandons the constant,
calling it his "greatest blunder."

Lemaître identifies this "cosmological constant" as a real physical entity: the **energy of vacuum in quantum theory!**

- It must be positive for the age of the universe to be consistent with data, meaning, *the expansion is accelerating*.
  - Experimentally confirmed 67 years later (High-Z Supernova Search).

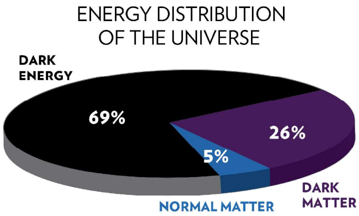
There was one issue. Lemaître, a Belgian priest, shows that GR describes an expanding universe; meaning, space-time itself had a "beginning." Einstein believes the universe must be static, so he adds a constant, trying to "fix" GR.

But Hubble's data confirms the expansion. Einstein abandons the constant, calling it his "greatest blunder."

Lemaître, on the other hand, identifies this "cosmological constant" as the real energy of vacuum in quantum theory.

He argues it must be positive for the age of the universe to be consistent with data, meaning, the expansion is accelerating. This is experimentally confirmed 67 years later.

Space is not empty!

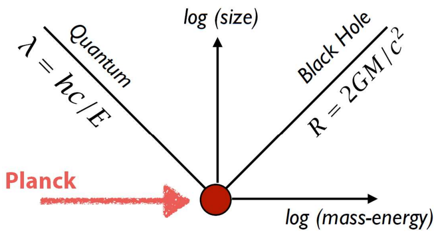


67 ∼ 74 % is "dark energy" of vacuum!

"No point is more central than this, that space is not empty, it is the seat of the most violent physics."

— J. A. Wheeler

- Quantum theory: all states are probabilistic.
- Vacuum: a state with an infinite number of virtual fields constantly popping in and out of existence.
- Space-time not well-defined at the smallest scales.



Original relation discovered by Matvei Bronstein

But why does empty space have any energy?

In quantum theory, there is no such thing as true "emptiness," because all quantum states are probabilistic.

Vacuum is a state that has an infinite number of virtual fields constantly popping in and out of existence.

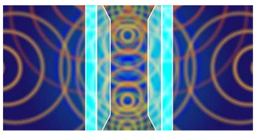
At the smallest scales, these virtual quanta are energetic enough to be black holes. Empty space-time itself is not a well-defined reality.

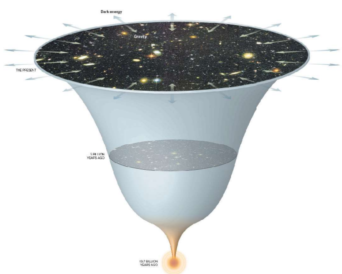
We can measure this energy of vacuum in a lab, and it matches our theories.

But if we scale this theory to the universe, it's 122 digits larger than the total energy in the universe.

The greatest failure in fundamental physics — Why does the universe exist?

- The energy of vacuum measured in a lab matches our theories!
- If we scale this theory to the cosmos, prediction is 122 orders of magnitude larger than the total energy in the universe.





- The cosmos needs a fine-tuned constant to be stable.
- Can our laws explain the full existence of the universe?
  - Fundamental parameters derived from first principles?
- "Anthropic selection" — the leading explanation today:
  - Out of infinitely many possible multiple universes, stable ones allowing our existence were "selected."
  - Multiverses are not empirically testable!

Furthermore, this is a vivid example of the "cosmic fine-tuning problem." If this value was not so inexplicably small, the universe could not be stable.

But if the laws of physics are to explain the full existence of the universe, it should be able to predict these constants from first principles. We can't just have arbitrary parameters that we can tune.

But the leading explanations we have today involve "anthropic selection":

Out of infinitely many possible multiple universes, the stable ones that allow our existence were "selected."
But multiverses are not empirically testable!

Space-time is *not* an absolute reality!

A foundational conflict: two fundamental theories, both accurate to 10+ significant figures!

- General relativity: a theory of space-time, as an absolute reality.
- Quantum mechanics: a theory of everything else — every particle, every other force known.

After 30 years of work from Einstein, to his deathbed, an unsolved question for 100 years...

- No "static" space-time. Probabilistic quantum states have energy — or mass ($E = mc^2$).
- The inertial reference frame – Newton's absolute space-time – dynamically dragged!
  - Remember, the gravitational field of a mass is a curvature in space-time itself.

Apache Point Observatory lunar laser ranging | Gravity Probe- B

Space-time might be relational: no absolute reality, no universal background for everyone.

- Only *quantum* relationships between events and observers are well-defined.
- Space-time may be an *emergent* phenomenon, "made out of" many quantum elements!

The substance of this quantum space-time is the seat of a foundational conflict. You see, space and time follow general relativity, whose framework describes an absolute reality.

Quantum mechanics governs everything else -- every particle, every other force known.

Recall there is no such thing as an "empty" space-time, because all quantum states are probabilistic.

These states have energy, and therefore mass.

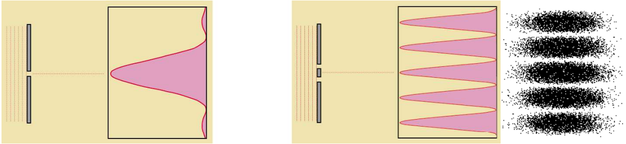
So the inertial reference frame -- Newton's absolute space-time -- is dynamically dragged by this quanta of mass!

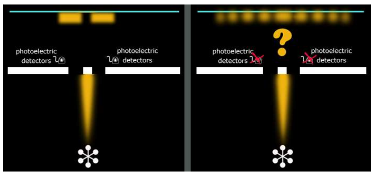
A likely path of reconciliation is that space-time might be relational. There is no absolute reality, no universal background for everyone. The only things well-defined are quantum relationships between events and observers.

Do quantum probabilities describe true *reality*?

Heisenberg's uncertainty principle for particles: $\Delta x\,\Delta p \;\geq\; \hbar/2$

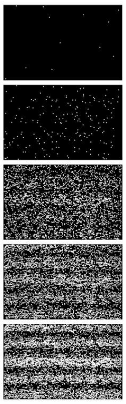
- One fewer dimension of information, or independent degree of freedom.





Each particle acts like it takes a superposition of paths.

But the probabilistic paths collapse if we try to detect them individually!



So if quantum relationships form the basis of space-time, do quantum probabilities describe true "reality"?

Forget about space-time for a second, and let's go back to conventional quantum, with particles.

There is a principle of irreducible uncertainty, when you try to measure position and momentum at the same time.

You have one fewer dimension of information, or independent degree of freedom.

If you shoot particles of light at a screen, and localize their position with a narrow slit, it makes the direction of momentum uncertain and probabilistic.

What if you put a detector over a slit to measure the path of each particle? The probabilities disappear.

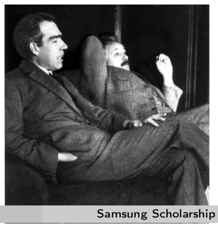
A great debate about the nature of reality...

Epistemic uncertainty

- The laws of physics are deterministic.
- There is an absolute underlying reality.
- We just do not know or observe the hidden information.

"I, at any rate, am convinced that God does not throw dice."

— Albert Einstein



Ontic indeterminacy

- Nature "has not decided on" a definite outcome "before it is observed."
- The probabilities of quantum mechanics, and the lack of definite information, are fundamental realities.

"Einstein, stop telling God what to do!"

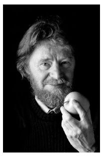
"Everything we call real is made of things that cannot be regarded as real."

— Niels Bohr

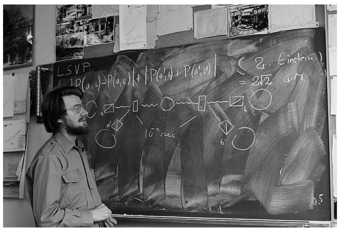
The possible interpretations: 1) Epistemic uncertainty – There is some absolute underlying reality, and the laws of physics are deterministic, but we do not know or observe the hidden information.

2) Ontic indeterminacy – Nature "has not decided on" any definite outcome. The probabilities, and the lack of definite information, are fundamental realities.

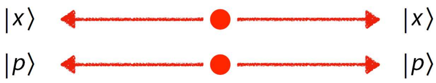
The referee: What is the total amount of information?



Bell's inequality



The Einstein-Podolsky-Rosen "paradox"



- If quantum indeterminacies are fundamental, both particles are part of a *single system* extended across the separation, sharing a smaller total info content.
- **Entanglement**: Measuring one particle is *not a degree of freedom independent* from the other one.
- *"Spooky action at a distance"*: One measurement instantly determines the uncertainty in the other — faster than light, faster than information can travel.
  - A violation of causality?

The adjudicating test is the total amount of information. This is quantified by Bell's inequality in an EPR test --

A source emits two particles in opposite directions, and position or momentum are measured at large separation.

If we really had fundamental indeterminacies, quantum mechanics says both particles are part of a single system extended across the large separation, sharing a smaller total information content.

If you measure one particle, that is not a degree of freedom independent from the other particle, because they are entangled.

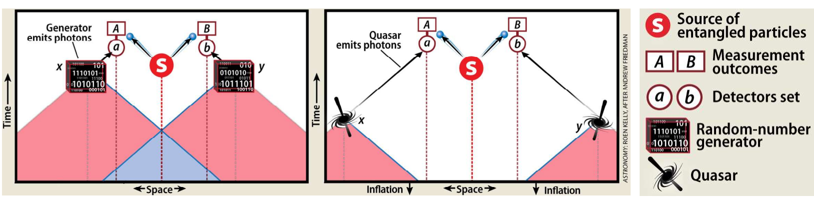
This means that one measurement can instantly determine the uncertainty in the other, faster than light, faster than information itself can travel.

Einstein called this "spooky action at a distance" and thought it would violate causality -- the consistent relationship between cause and effect in relativity.

Cosmic tests of free will, determinism, and absolute causality

Over decades of Bell tests, nature has overwhelmingly favored fundamental indeterminacy. But...

- Free will assumed: We can "randomly" choose what to measure — say, x or p — each time.
  - Circular argument: If the laws of nature are deterministic, we have no such freedom of choice.
- Random-number "choices": Could both be "determined" by common events in the past?
- These loopholes may be avoided by "choosing" with signals from distant cosmic phenomena.
- Space-time diagrams: Are these causal structures and symmetries exact and absolute?



In extensive Bell tests over several decades, there is now overwhelming evidence that nature is fundamentally indeterminate. But a few loopholes remain:

1) Free will was assumed: We can "randomly" choose what to measure -- position or momentum -- each time.

But if the laws of nature are deterministic, they would also determine our choices. So the argument is circular.

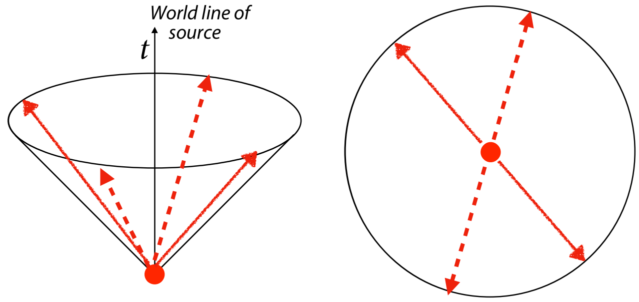
2) What if both choices were influenced by common events in the past?

Both these loopholes might be avoided by using signals from distant cosmic phenomena to make the choice.

3) But these are diagrams drawn in space-time. Are the causal structures and symmetries of space-time exact and absolute?

A bridge connecting foundational principles of reality...

- Study the structures and symmetries of quantum indeterminancies in space-time itself!
- **Relativity and QM**: *Entangled particles of light actually follow exact causal structures.*
- Probe correlations in space-time, with **world lines** and **light cones** as building blocks.



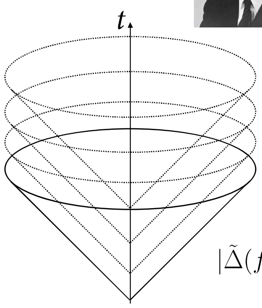
So now we have to consider quantum indeterminacies in space-time itself.

Entangled particles of light actually follow causal structures.

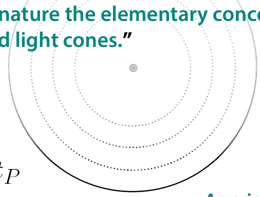
A bridge connecting foundational principles of reality...

"Just as the proper recognition of this atomicity requires in the electromagnetic theory a modification in the use of the field concept equivalent to the introduction of the concept of action at a distance, so it would appear that **in the gravitational theory we should be able in principle to dispense with the concepts of space and time and take as the basis of our description of nature the elementary concepts of world line and light cones.**"

— **J. A. Wheeler**



$|\tilde{\Delta}(f)|^2 \approx t_P$

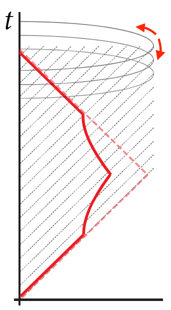


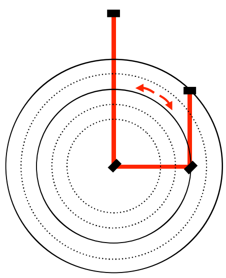
American Philosophical Society

Can we test this structure, and the "reality" of space-time?

Design for an empirical probe: a bent Michelson interferometer

- Sensitivity needed: $1/10{,}000{,}000$ of a single atom over the length of a football field.
- Sampling rate: Must measure faster than the timescale of light travel across the apparatus.





$$\langle \Delta x_\perp^2 \rangle_P = \ell_P L$$
$$= \text{PSD } t_P L^2$$
$$\times \text{ Bandwidth } c/L$$

$$\text{where PSD} = \tilde{h}^2(f) \cdot L^2$$
$$h \equiv \delta L / L$$

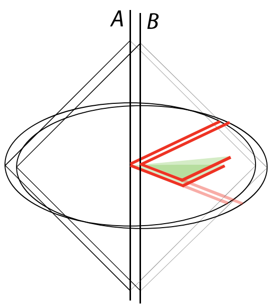
$$\tilde{h}^2(f) \approx t_P$$
$$\equiv \int_{-\infty}^{\infty} \left\langle \frac{\delta L_A(t)}{L} \frac{\delta L_B(t-\tau)}{L} \right\rangle_t e^{-2\pi i \tau f}\, d\tau$$

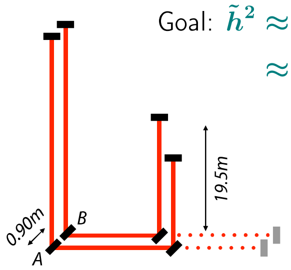
We can use Michelson's interferometer, but with a bend, so the light path probes through the causal structures.

Sensitivity needed: 1 over 10 million of an atom over the length of a football field, measured faster than light can travel across the device.

Design for an empirical probe: a bent Michelson interferometer

- Planck: If the cosmic horizon was scaled to a grain of silt, what a grain of silt would become.
- Superluminal sampling: Measurements must be made before quantum states decohere.





Goal: $\tilde{h}^2 \approx t_P \equiv \sqrt{\hbar G / c^5}$

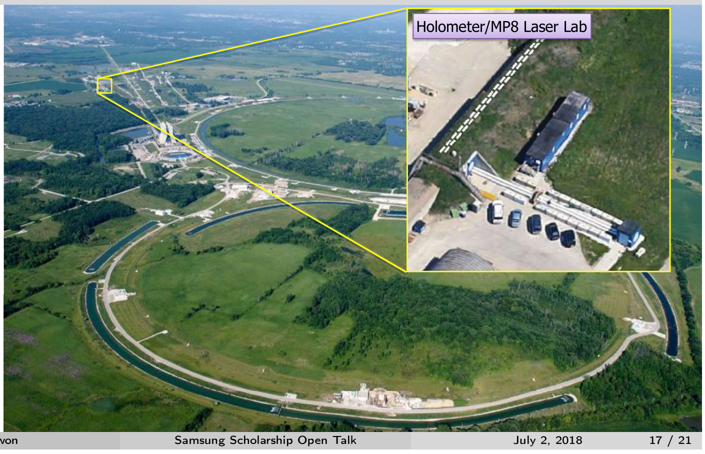
$$\approx (Nf)^{-1} \approx 10^{-44}\,\text{s}$$

Use $f \approx 10^{15}$ Hz photons.

Need to average over $N \approx 10^{29}$ photons.

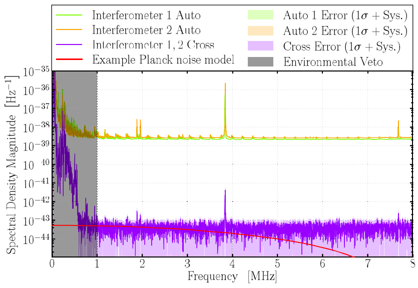
We need 10^29 particles of light.

The Fermilab Holometer!

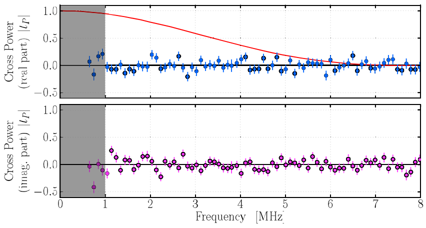


We built this experiment at Fermilab, the Holometer.

First-generation Holometer: sensitivity demonstrated, null control at 0.1 Planck scale



- 145 hour data — PRL **117**, 111102 (2016)
- 704 hour data — CQG **34**, 165005 (2017)
- Instrumentation — CQG **34**, 065005 (2017)
- *Dimensionless strain*, normalized to $L = 39\,\mathrm{m}$.

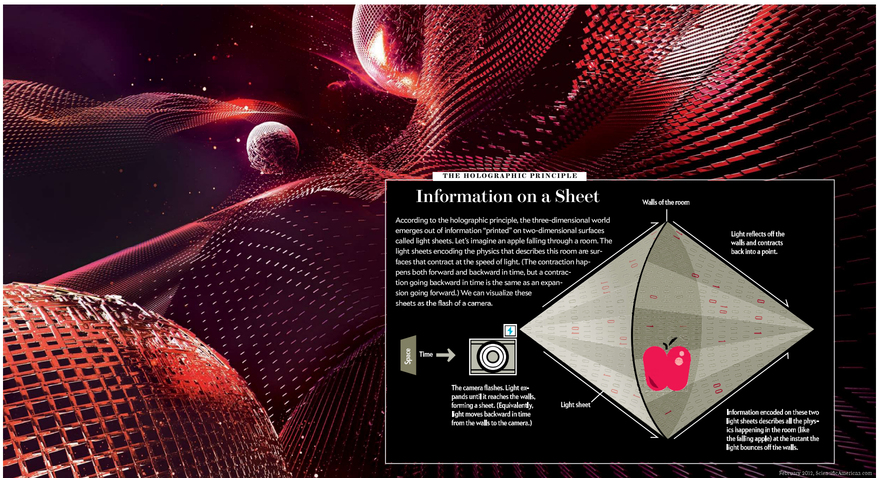


- **Left:** Independent bins at 1.9 kHz resolution.
- **Right:** Rebinned to 100 kHz, Planck units.
- Example spectrum of $t_P\,\mathrm{sinc}^2(\pi f L/c)$, the auto-correlation of a flat "boxcar" response at scale L.
- ***Second-Generation Holometer operational, with similar systematics and backgrounds.***

We've demonstrated that our clocks and rulers are more than sensitive enough. We are currently collecting real data.

If there is an irreducible quantum uncertainty above our limit, it means space-time itself is pixelating like a limited-resolution digital photograph.

The correlated shapes in this pixelation will tells us the structure of quantum space-time.



Just like a compressed JPEG photograph, this uncertainty reflects the information content of space-time. Recall the "background space-time" -- a 3+1 dimensional coordinate system.

But if there is this fundamental quantum uncertainty in space-time at our level of sensitivity, that means there is one fewer dimension of information.

It's similar to how the uncertainty principle gives us one fewer independent degree of freedom.

This means that the universe we live in is like a hologram -- we perceive three dimensions, but really, there is only two dimensions' worth of information.

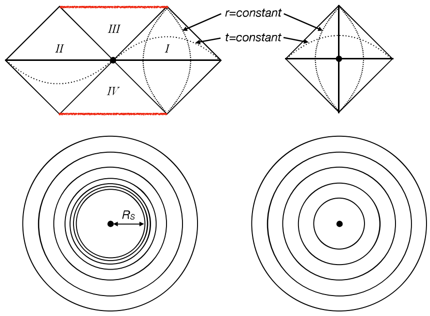
We live in a holographic universe — a 2D limit on information content

The entropy of a black hole — the amount of information in the system — is proportional to the 2D "surface area" of its horizon! Standard entropy scales with system size — 3D volume.

$$S_{BH} = \frac{kA}{4\ell_P^2}$$

Any system with higher information density has too much energy and will gravitationally collapse into a black hole — objects "made out of" pure space-time.

In the current standard theory, the energy of vacuum — or "empty space" — in a Gyeonggi-do sized sphere will be sufficient to bring that fate!



The limits of empirical epistemology, and the integrity of science.

We are observers on the fabric of space-time. We are bound by its structure, "reality," and foundational principles, as we ask:

- How does our stable universe exist?
- Are the laws of nature deterministic?
- What is the reality of space-time?
  - Are space and time themselves fundamentally indeterminate? Are causal structures absolute?
  - Is the "arrow of time" explained by thermodynamics in the full quantum system that includes space-time?
  - Does time have a beginning without a boundary, with no extrinsic domain or cause?

Our epistemology is circular:

- We empirically "confirm" a theory's predictions.
- The theory describes the "reality" of our space, time, and free choice.

Many proposed explanations to our open problems — and our existence — are purely mathematical:

- A landscape of string theories in the multiverse.
- A theory that matches existing observations in nature, and is elegant, simple, and "natural," but is beyond the empirical regime, or makes predictions that contain tunable parameters that cannot be falsified.

What fundamental limits will we have to accept? What are the boundaries of scientific truth?

We are building a team for the next stage of the Holometer program. Join us!

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This sounds crazy. But there is actually strong indirect evidence for this.

We know that the entropy of a black hole, the amount of information in it, is proportional to the 2D surface area, and not its 3D volume.

There is a holographic upper limit on the information density of the universe, because anything denser will have too much energy and collapse into a black hole.

So this connects back to the energy of empty space!

We are observers on the fabric of space-time. We are bound by its structure and reality.

Our epistemology is limited by the foundational principles of its governing laws.

What we can learn about its ontology holds the answer to these most essential questions about our existence: all these ones we've mentioned, and –

The "arrow of time," and the beginning of time.

We must carefully think about the boundaries of scientific truth.

If we experimentally confirm a theory, but it describes the "reality" of our space, time, and free choice, what are the limits of this circular epistemology?

Also, more and more theoretical solutions to our remaining open problems are entirely in the mathematical realm.

If the best explanation for our particular existence is:

1) a landscape of string theories in the multiverse...

2) or, say, a theory that matches existing observations in nature, and is elegant, simple, and "natural," but is beyond the empirical regime, or makes predictions containing tunable parameters that cannot be falsified...

We may have to accept that we have encountered fundamental limits, because the integrity of science is more important than our hubris.