The Fermilab Holometer: Is the universe a hologram?

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Ask-a-Scientist Public Lecture

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$$F = ma$$

A law of nature?

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

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

Oscillations of a pendulum "take equal time," measured with a pulse.

Soon thereafter, pulses are measured with pendulums.

Modern clocks are also based on oscillators!

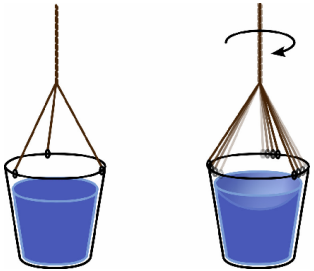
$$F(t) = m\,a(t)$$

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

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

Time becomes an *untestable* mathematical axiom.

Absolute space?

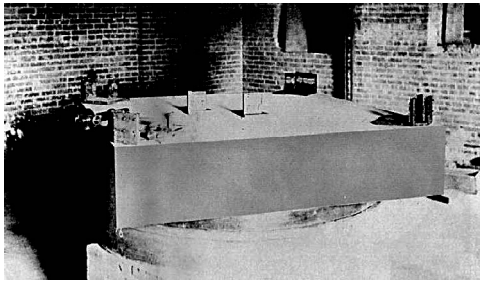


Newton: Local rotation agrees with measurements against distant stars.

There must be a universal global inertial frame of reference.

Modern cosmology (big bang + inflation) still has a "preferred" reference frame.

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



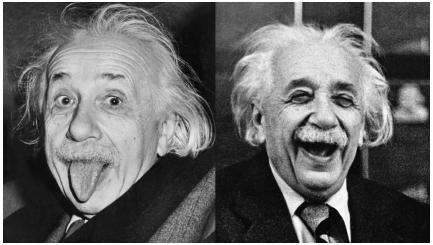
Michelson: The speed of light is independent of any observer frame in space-time.

There can be no background against which to measure it.

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

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* (or, a curvature thereof). 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.

The expanding universe, 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.

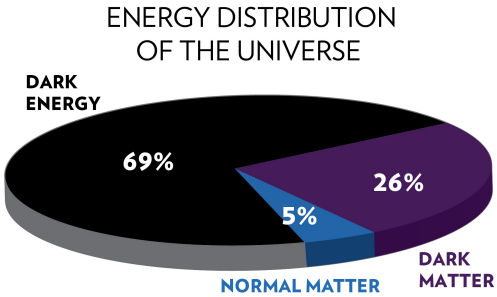
Hubble's data confirms the expansion.

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).

Space is not empty!

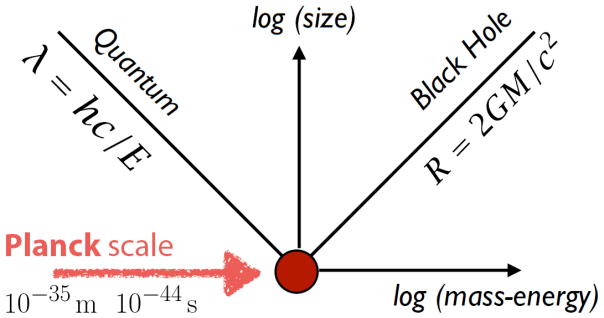


67 ∼ 74 % is "dark energy" of vacuum!

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

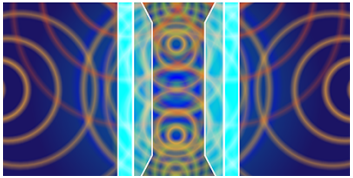
— J. A. Wheeler

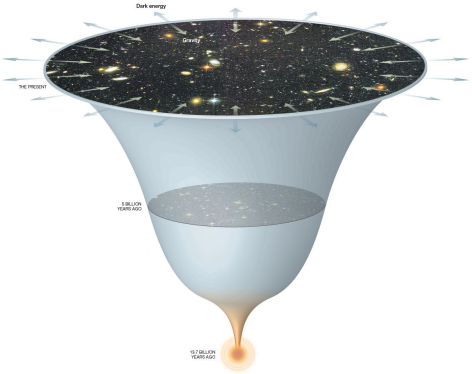
- Quantum theory: all states are probabilistic.
- Vacuum: a state with an infinite number of virtual fields constantly popping in and out of existence.
- Space-time not well-defined at the smallest scales.



Original relation discovered by Matvei Bronstein

- 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.





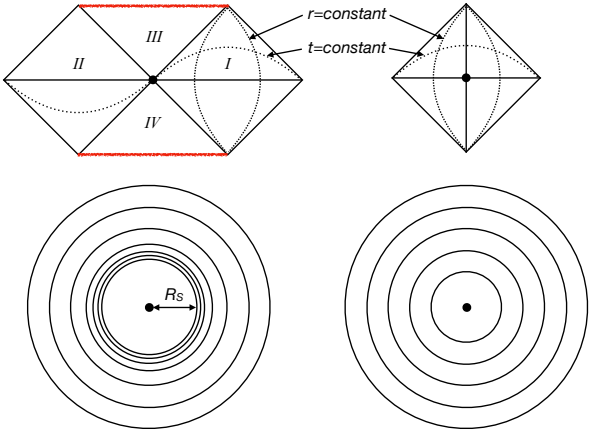
- The formation of a structured cosmos is dependent on a seemingly arbitrary fine-tuned constant.
- Can our laws explain the existence of the universe?
- "Anthropic selection" as a proposed solution:
  - Out of infinitely many possible multiple universes, stable ones allowing our existence were "selected."
  - Probably not an empirically testable hypothesis!

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 current standard theory, the energy of vacuum — or "empty space" — in a small 3D world (or sphere) that covers half of Lake Michigan will bring that fate!



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...

- All quantum states are probabilistic. They carry energy — or mass ($E = mc^2$).
- Any mass curves space-time (gravity).
- A non-static mass-energy will dynamically drag the inertial reference frame — so now Newton's absolute space is probabilistic?

Apache Point Observatory lunar laser ranging

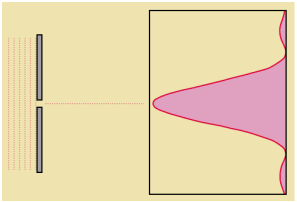
Gravity Probe- B

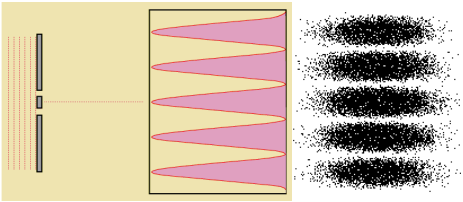
Space-time might be relational: no absolute reality, no universal background for everyone.

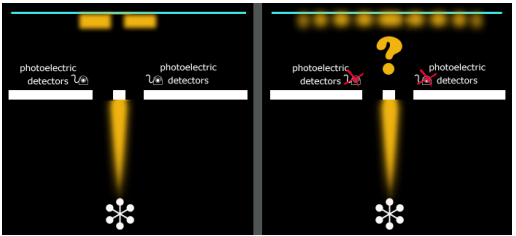
- Only *quantum* relationships between events and observers are well-defined.
- Space-time may be an *emergent* phenomenon, "made out of" many quantum elements!

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

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

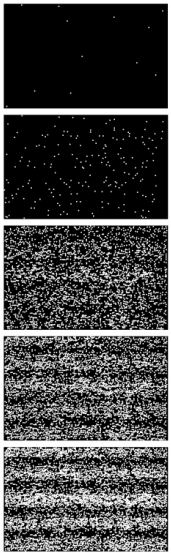






Each particle acts like it takes a superposition of paths.

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



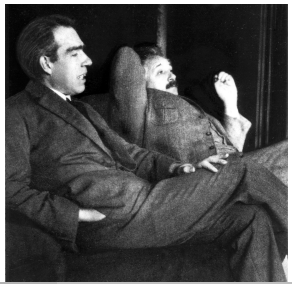
Epistemic

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

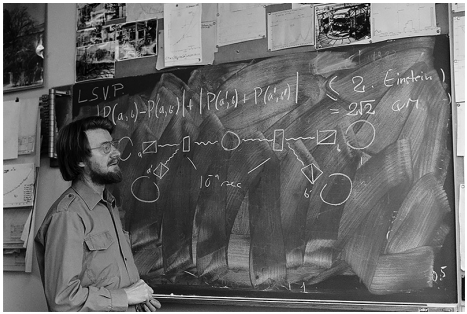
- Nature "has not decided on" a definite outcome "before it is observed."
- The probabilities of quantum mechanics, and the lack of definite information, are fundamental realities.

"Einstein, stop telling God what to do!"

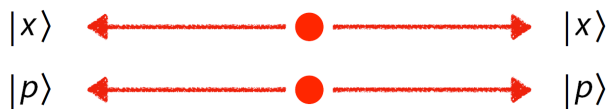
"Everything we call real is made of things that cannot be regarded as real."

— Niels Bohr

Bell's inequality



The Einstein-Podolsky-Rosen "paradox"

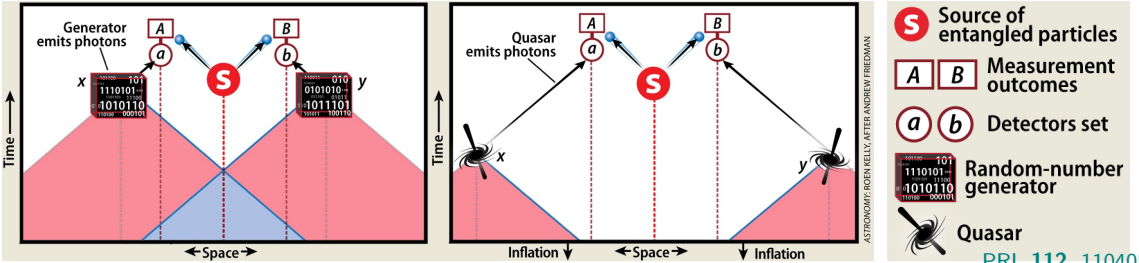


- If quantum indeterminacies are fundamental, both particles are part of a *single system* extended across the separation, sharing a smaller total info content.
- **Entanglement**: Measuring one particle is *not a degree of freedom independent* from the other one.
- ***"Spooky action at a distance"***: One measurement instantly determines the uncertainty in the other — faster than light, faster than information can travel.
  - A violation of causality? No!

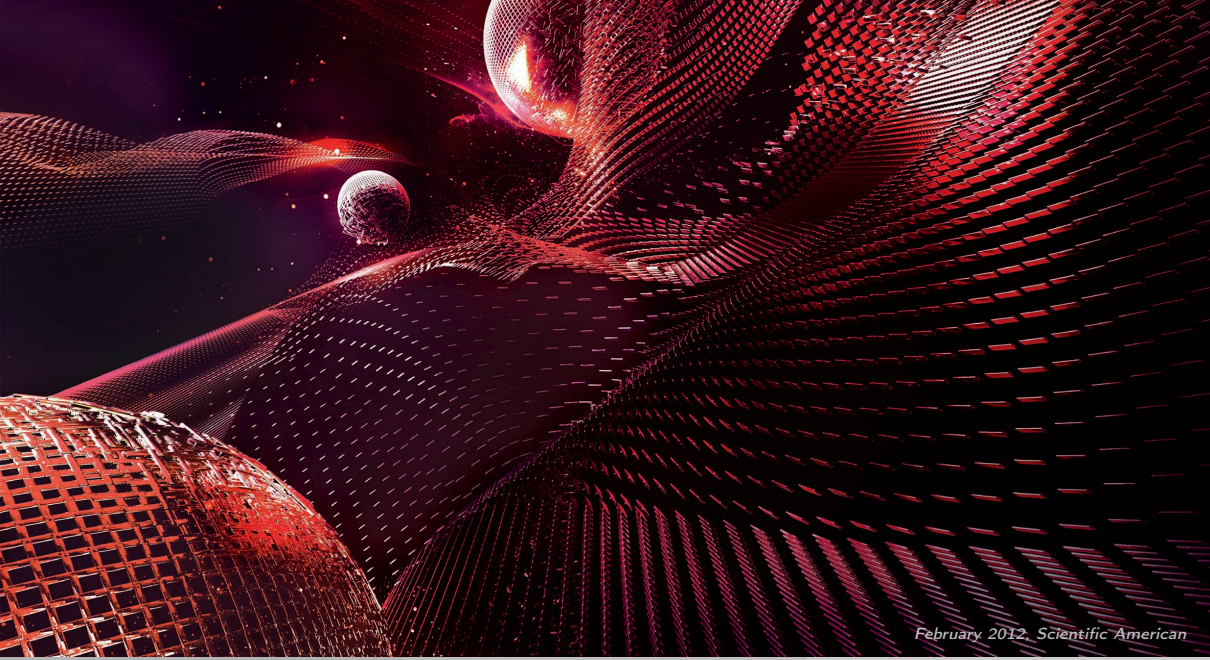
A final verdict depends on quantum space-time! Comes back to understanding foundations.

Decades of Bell tests have overwhelmingly pointed towards a fundamental indeterminacy. But...

- Can scientists "randomly" choose which observable to measure — say, x or p — each time?
  - "Free Will Theorem": This is connected to whether the laws of nature are deterministic!
- Random-number generators? Both could be "determined" by common events in the past.
- Cosmic Bell tests: "Choices" set by signals from "causally disconnected" cosmic phenomena.
- Holographic space-time: In a deeper foundation, are these causal structures still absolute?



PRL **112**, 110405



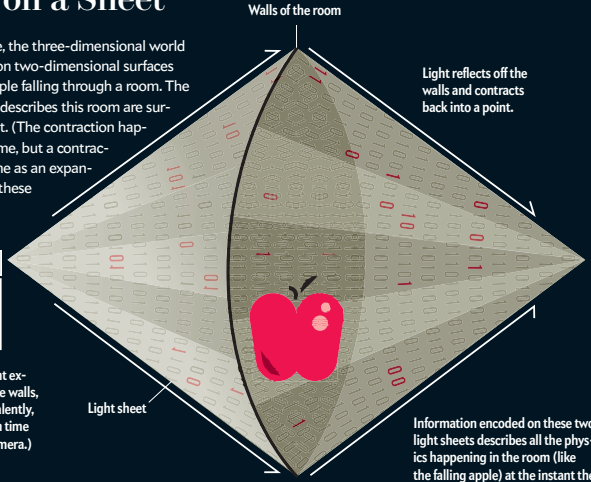
February 2012, Scientific American

THE HOLOGRAPHIC PRINCIPLE

Information on a Sheet

According to the holographic principle, the three-dimensional world emerges out of information "printed" on two-dimensional surfaces called light sheets. Let's imagine an apple falling through a room. The light sheets encoding the physics that describes this room are surfaces that contract at the speed of light. (The contraction happens both forward and backward in time, but a contraction going backward in time is the same as an expansion going forward.) We can visualize these sheets as the flash of a camera.

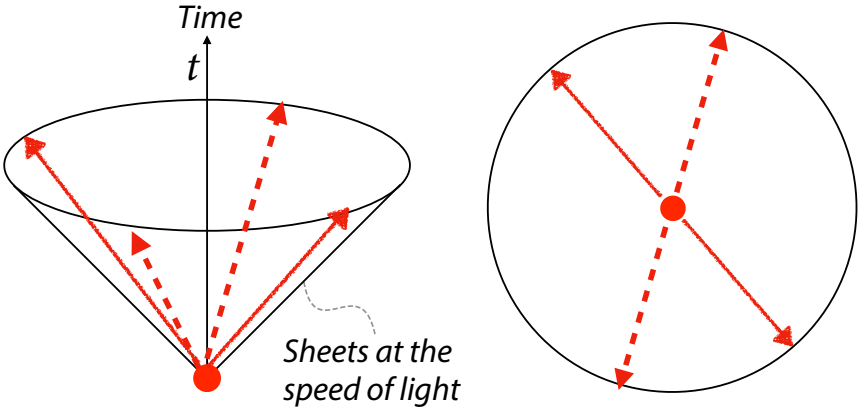
The camera flashes. Light expands until it reaches the walls, forming a sheet. (Equivalently, light moves backward in time from the walls to the camera.)



February 2012, Scientific American

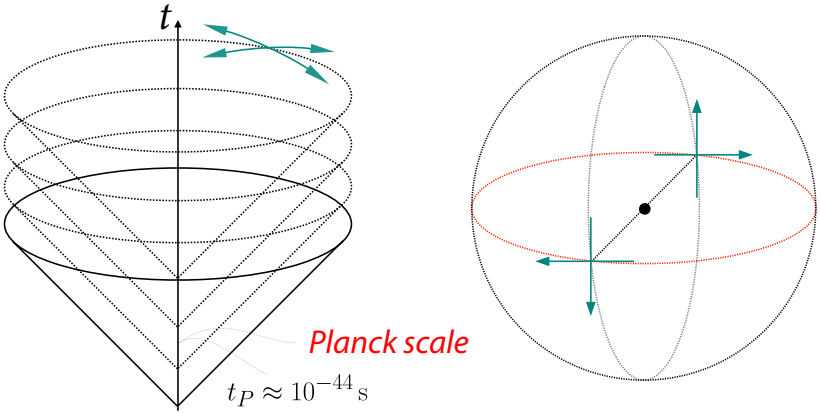
How to test holographic space-time?

- Our basic hypothesis: Connect quantum entanglement + relativistic structures in space-time.
- When entangled particles of light are emitted, they actually follow light cone structures.
- These building blocks may have directional uncertainties, as do Newton's reference frames!

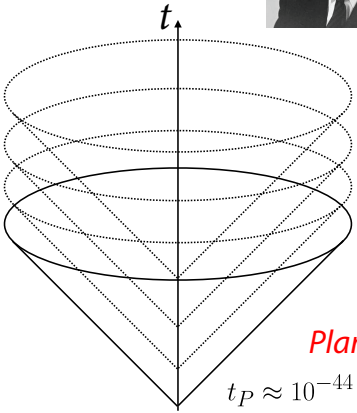


Holographic space-time — spooky signatures?

- *"Spooky action at a distance"*: Entangled fluctuations, superluminal pure imaginary spectra?
- The boundary of a light cone is a sphere in 3D space, with **two** independent rotational axes.
- Entanglement along these causal structures may lead to holographic reduction of information!



A simple vision prefigured circa 1950...



"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

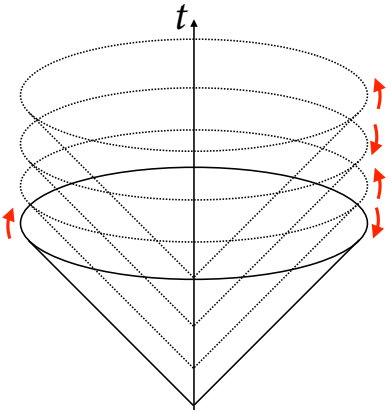
Planck scale

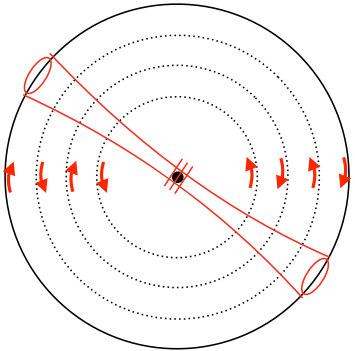
$t_P \approx 10^{-44}\,\mathrm{s} \qquad \ell_P \approx 10^{-35}\,\mathrm{m}$

American Philosophical Society

The Planck scale is *really* small, but the fluctuations may accumulate!

- Planck: If the cosmic horizon was scaled to a grain of silt, what a grain of silt would become.
- Let's imagine random steps of $\ell_P \approx 10^{-35}\,\mathrm{m}$ every $t_P \approx 10^{-44}\,\mathrm{s}$, drifting from zero average.
- Variance grows as $\sqrt{\#\,\mathrm{steps}}$ — for a measurement reaching Andromeda, 1/100th of a hair!





At a scale of

$$L = ct$$

$$c = 3 \times 10^8\,\mathrm{m/s}$$

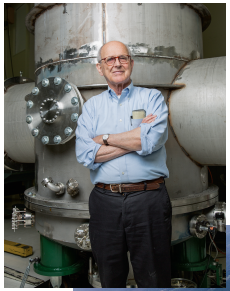
$$\left\langle \Delta x_\perp^2 \right\rangle_P = \ell_P L$$

$$\left\langle \Delta\theta^2 \right\rangle_P = \ell_P / ct$$

Can we really measure directional uncertainties at this sensitivity?

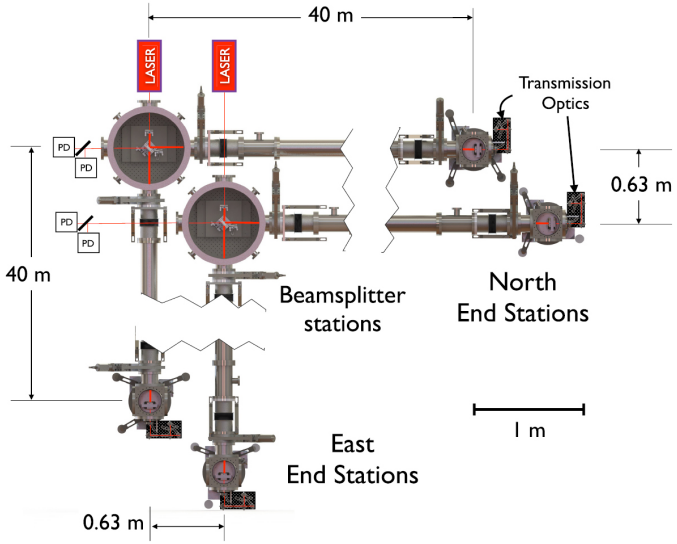
Measuring the rotation of the Earth with light traveling in two directions around a loop.
Albert Michelson, winter 1924, suburban Chicago.

Michelson interferometers: the only measurement apparatuses with this kind of sensitivity

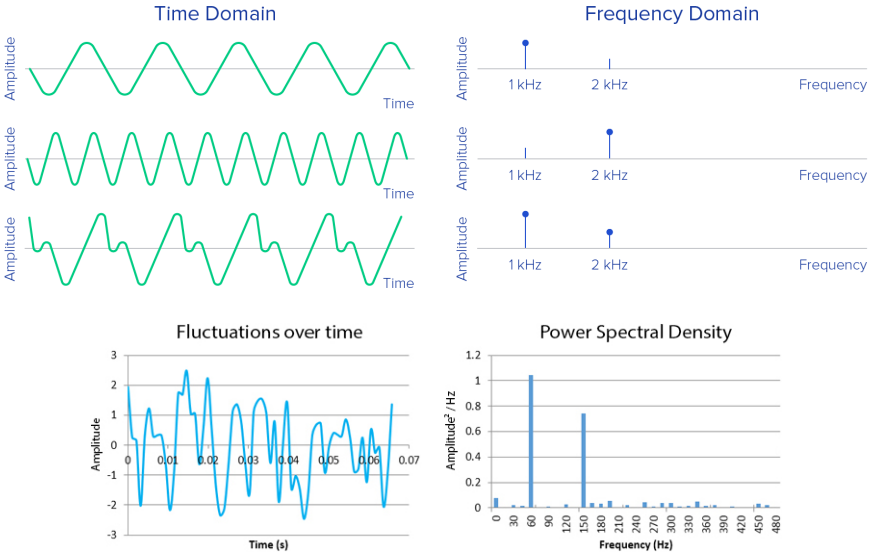


LIGO ⟶ Holometer

Dick Gustafson (Michigan)
Samuel Waldman (SpaceX)
Rainer Weiss (MIT)

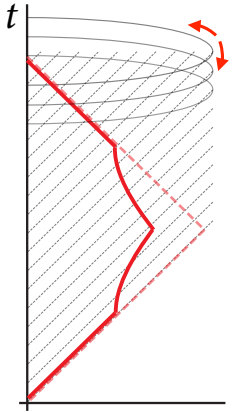


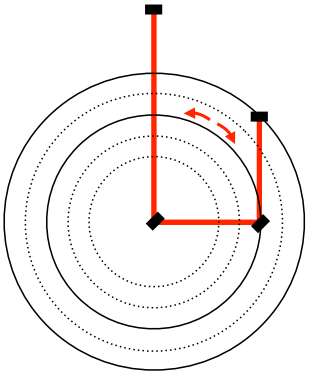
Interferometer signals: time-stream fluctuations measured → spectra of variance per frequency



Experimental design: a bent Michelson interferometer

- Sensitivity needed: $1/100{,}000{,}000$ of an atom, measuring a space-time system 40 m in scale.
- In $h \equiv \delta L/L$, fluctuation variance or ***power*** per each frequency (***spectral density***) is $\approx t_P$.
- Add up fluctuation measured at a broad range of frequencies, with superluminal **bandwidth**.





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

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

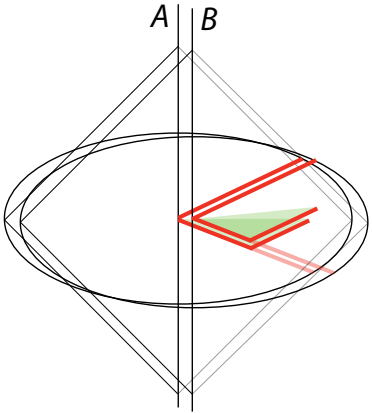
$$\boldsymbol{h \equiv \delta L / L}$$

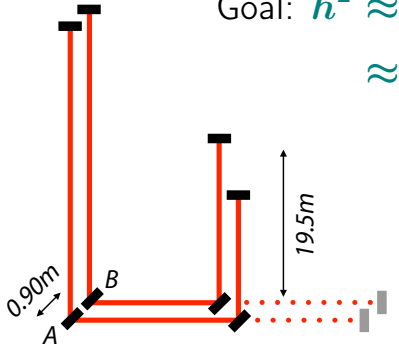
$$\boldsymbol{\tilde{h}^2(f) \approx t_P}$$

$$\equiv \int_{-\infty}^{\infty} \langle \delta h_A(t)\, \delta h_B(t) \rangle_t \; e^{-2\pi i \tau f} \, d\tau$$

Experimental design: two overlapping interferometers

- Sampling rate: Much faster than the timescale of light travel across the system ($\approx 8\,\mathrm{MHz}$).
- The space-time information measured is correlated, but instrumental noise is uncorrelated!
- Largest noise is quantum uncertainty in each particle of light. Need to average 10^{29} photons!





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

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

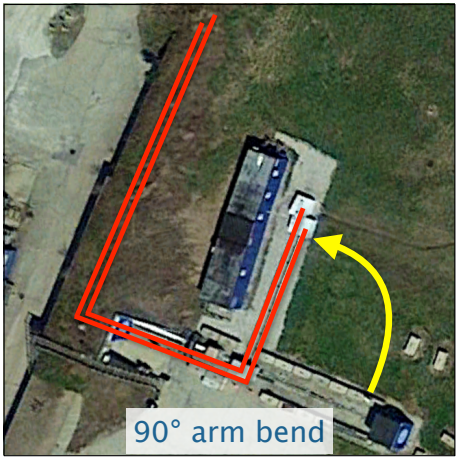
Use $f \approx 10^{15}$ Hz photons.

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

Experimental design: two different configurations (null control needed)

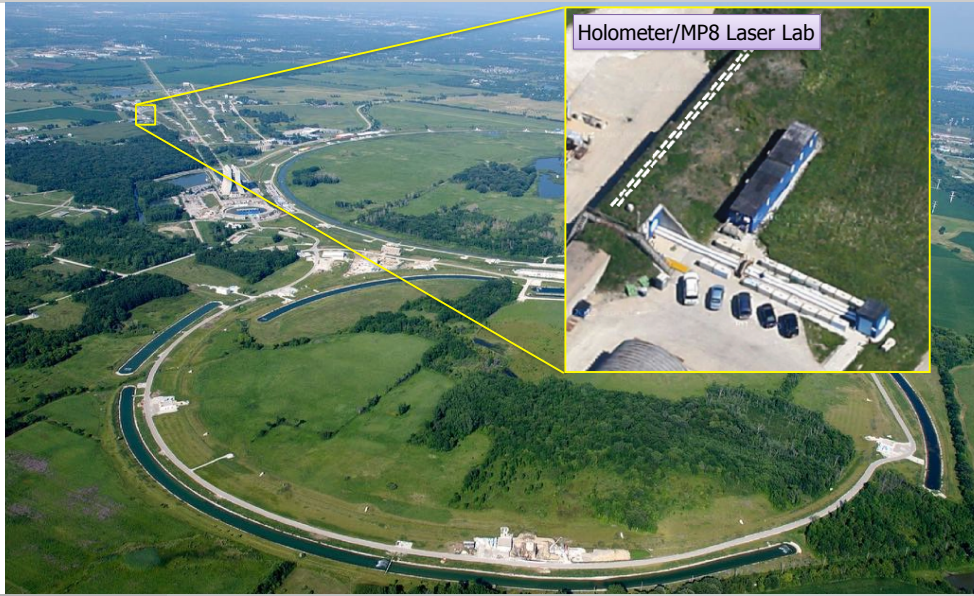
First-generation Holometer (2011-2016)

Second-generation Holometer (2017-present)

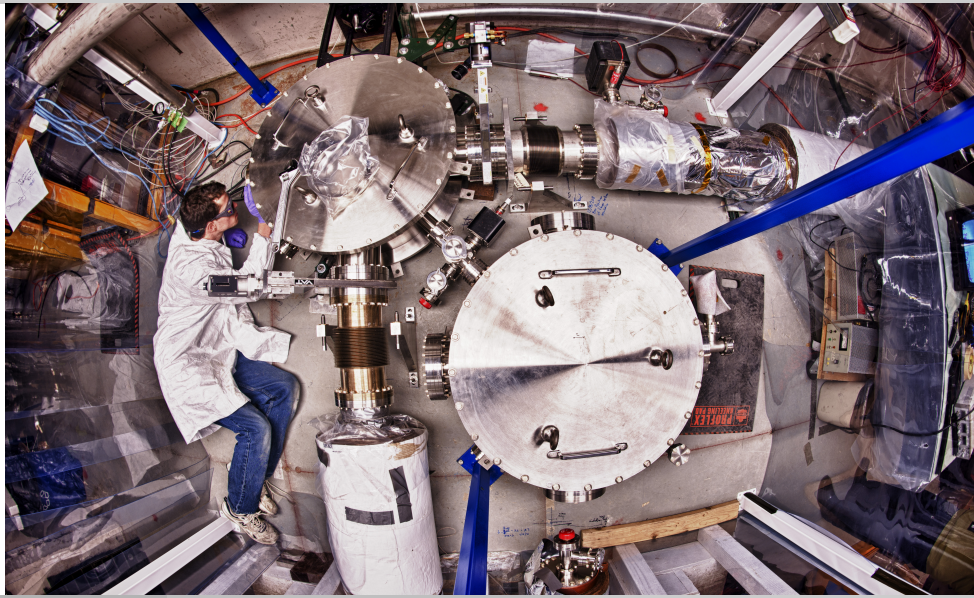


Bend mirror added. Unmodified: optics, electronics, control system, and data acquisition chain.

The Fermilab Holometer



The Fermilab Holometer



INPUT SIDE

Lasers & Active Optics

- Correlated optical intensity noise
- Correlated optical phase noise

Continuously measured during data acquisition

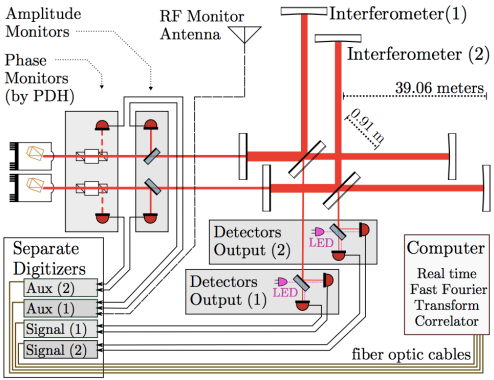
OUTPUT SIDE

Detectors & Readout Electronics

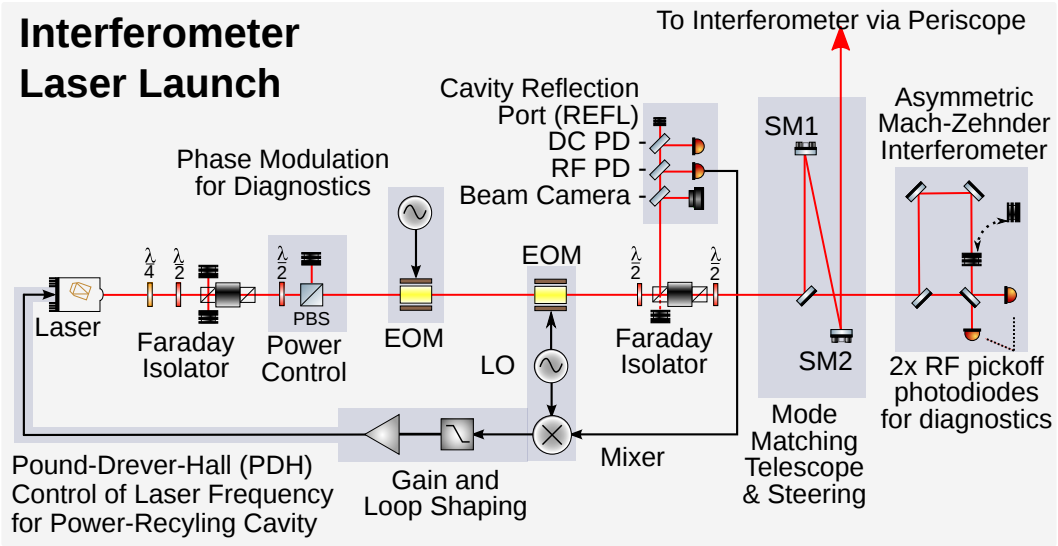
- Correlated electronics noise
- Cross-channel signal leakage

Measured offline using optical sources of independent white noise (incandescent light bulbs)

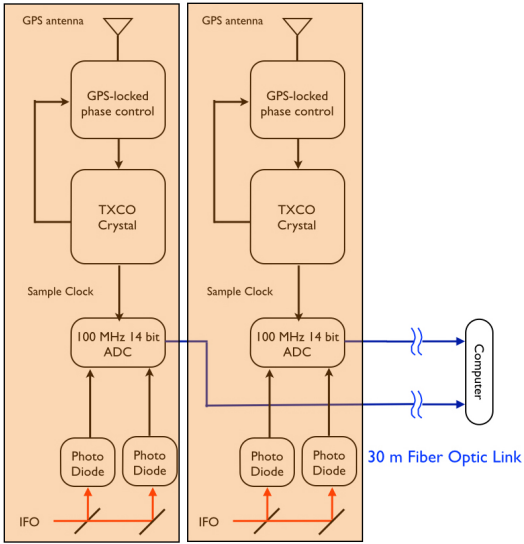
Realtime Monitoring of Laser Noise and Radio-Frequency (RF) Environment



Four RF environmental channels are cross-correlated with the interferometer output channels (8x8 correlation matrix)


Interferometer
Laser Launch
To Interferometer via Periscope
Cavity Reflection
Port (REFL)
DC PD
RF PD
Beam Camera
Phase Modulation
for Diagnostics
SM1
Asymmetric
Mach-Zehnder
Interferometer
EOM
Laser
Faraday
Isolator
PBS
Power
Control
EOM
LO
Faraday
Isolator
SM2
2x RF pickoff
photodiodes
for diagnostics
Mode
Matching
Telescope
& Steering
Mixer
Pound-Drever-Hall (PDH)
Control of Laser Frequency
for Power-Recyling Cavity
Gain and
Loop Shaping

Output side: isolated high-speed data acquisition systems and sampling clocks



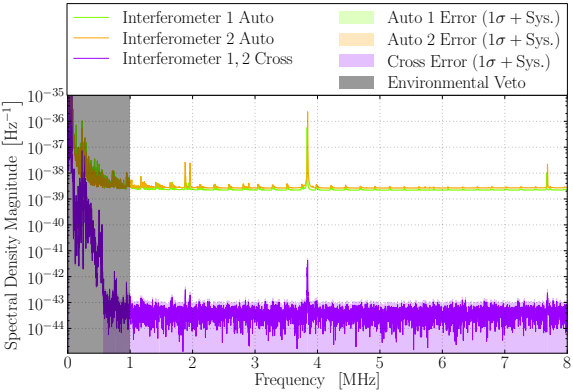
Each ADC (analog-to-digital converter) unit individually synchronized to a GPS-provided clocking signal.

Relative drift of sampling clocks follow a normal distribution of width ~ 10 ns, limiting inter-channel decorrelation to less than 15%.

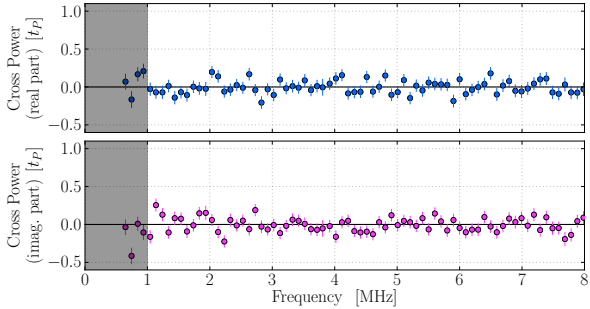
Cross-power spectral density (CSD) calculated from real-time Fast Fourier Transform (FFT).

This converts time-stream fluctuations into variance per frequency.

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)
- Variance in $\delta L/L$, normalized to $L = 39\,\mathrm{m}$.

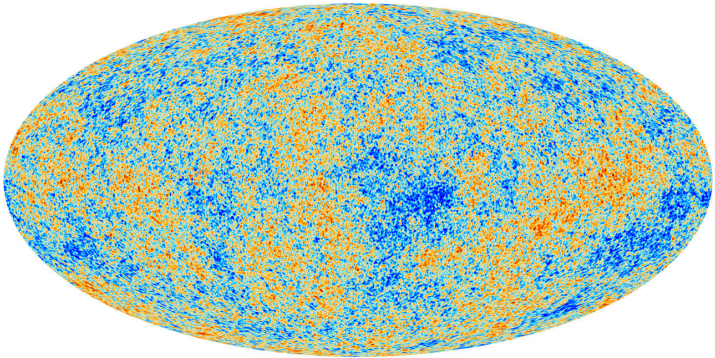


- **Left:** Independent bins at 1.9 kHz resolution.
- **Right:** Rebinned to 100 kHz, Planck units.
- ***If there was a signal, our rulers and clocks have enough resolution to measure it.***
- First show zero, then measure nonzero values in the second-generation rotation sensitive configuration!

Preview of Second-generation Preliminary Data

Holographic signatures staring at us in the sky, in the cosmic microwave background?

Cosmic structure is a relic of quantum fluctuations during inflation



The specific pattern is an intact image of a primordial quantum state

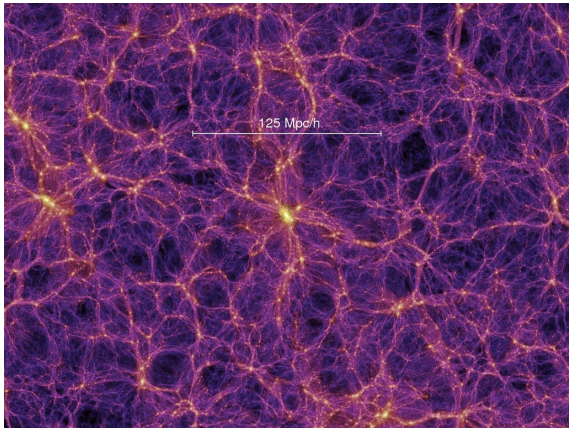
Its correlations contain information about the quantum state

Primordial correlations in space-time curvature potential remain mostly intact until a structure goes nonlinear

Potential can be probed by galaxy density in the linear regime, on scales << CMB

Orbital motion mixes away primordial ***entanglement*** *(antipodal) on scales smaller than the cosmic web*

$$L_* \approx 40\mathrm{Mpc}$$



Cosmology slides
adapted from C. J. Hogan

Spooky patterns may also show up in 3D maps of galaxy density! (Dark Energy Survey)

The National Science Foundation's Cerro Tololo Inter-American Observatory in Chile. Photo by Guillaume Doyen "AstroGuigeek"

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