Measurement of Quantum Fluctuations in Geometry

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SLAC, Experimental Seminar

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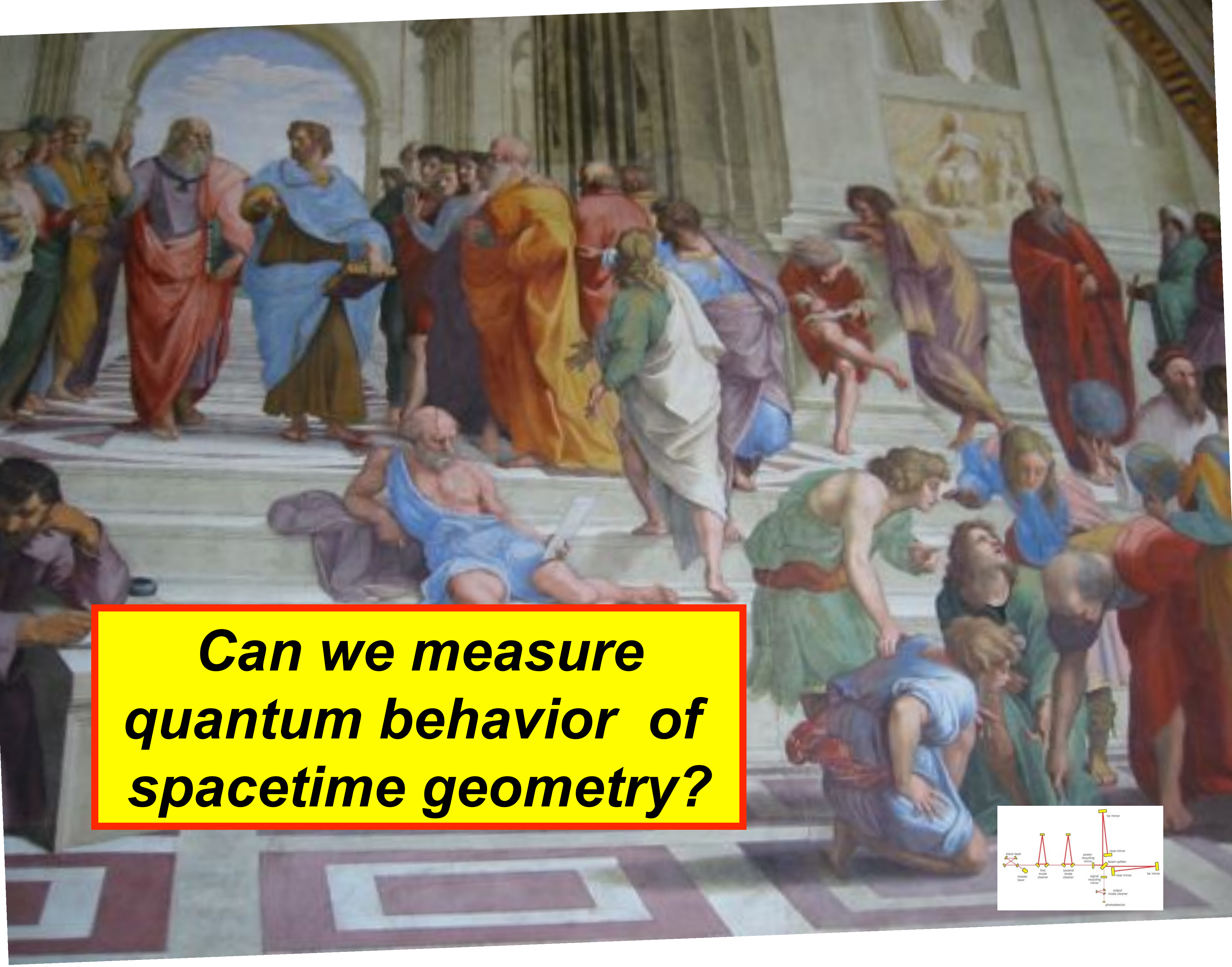


Can we measure quantum behavior of spacetime geometry?

Holographic Quantum Geometry

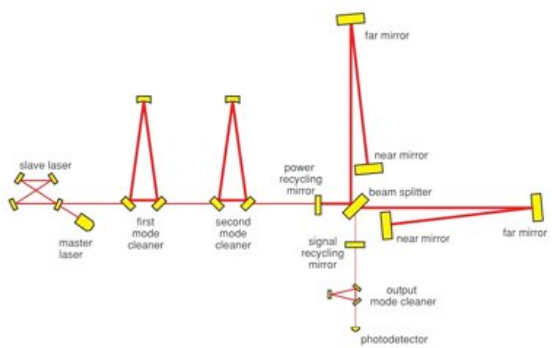
- Spacetime is a quantum system
- Standard field quantization in classical spacetime creates "spacetime foam" at Planck length,

$$l_P = \sqrt{\hbar G_N / c^3} = 1.616 \times 10^{-33}\mathrm{cm}$$

- **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

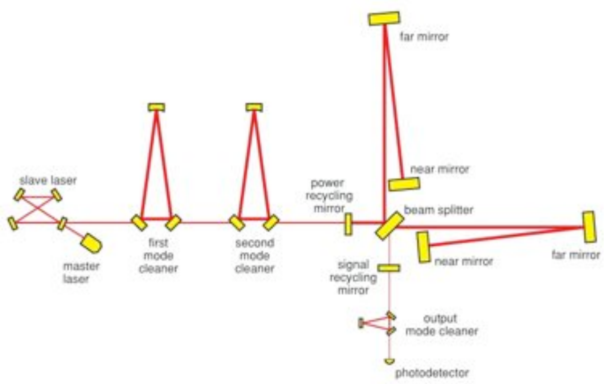
How does quantum geometry affect quantum fields?

- 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

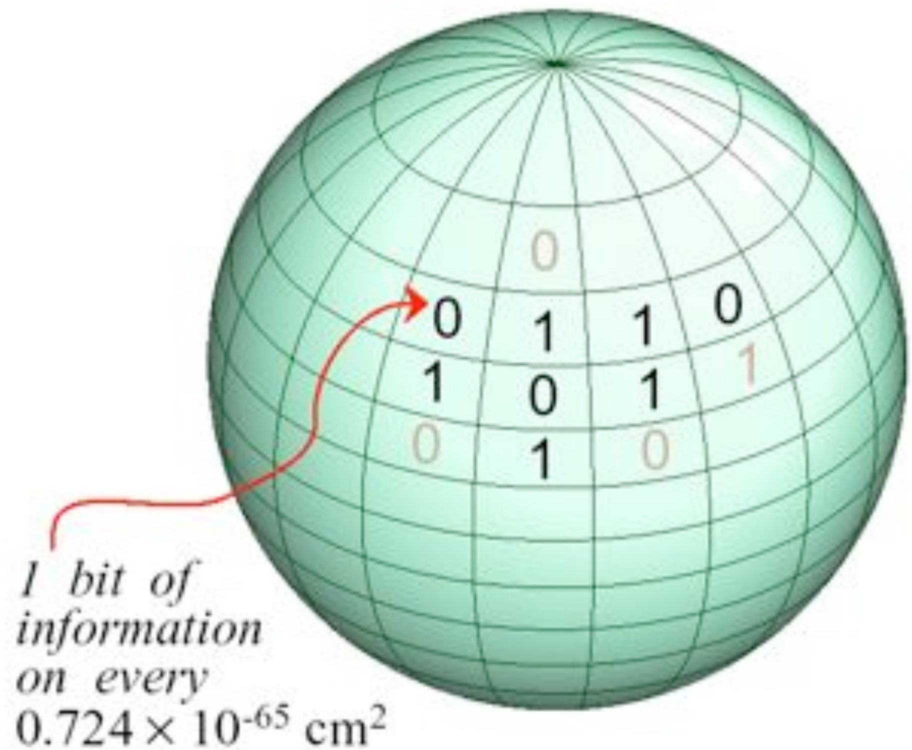
- Traditional experimental approach to small lengths/large energies is the high energy frontier-- accelerators
- For quantum geometry: position measurements by interferometers designed for gravitational wave detection (narrow wavefunction of macroscopic mass position)
- "holographic geometry" defined 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
- **arXiv:0712.3419,** to appear in PRD



"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 $S = A/l_P^2 4 \ln 2$
- 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

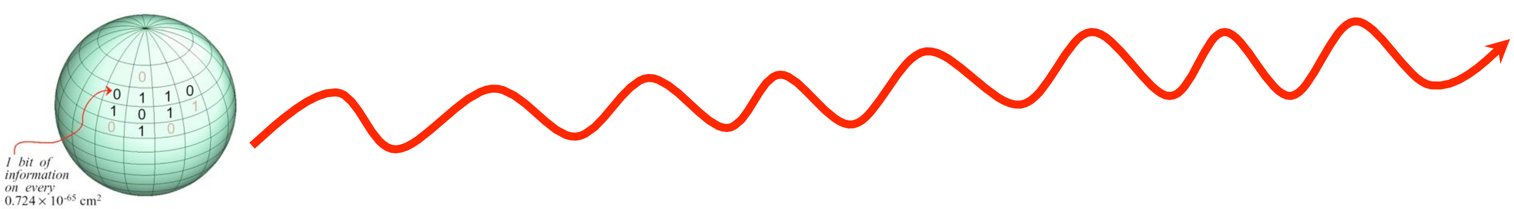
Beckenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Padmanabhan

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 is a deep reason connected with microscopic degrees of freedom of spacetime encoded on the surface?

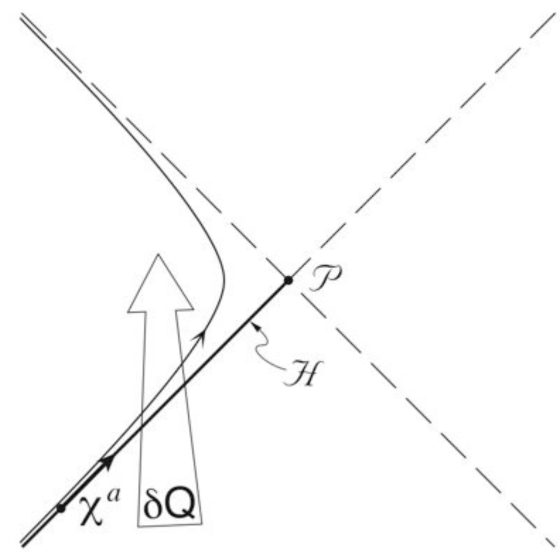
Holography 2: Black Hole Evaporation

- 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

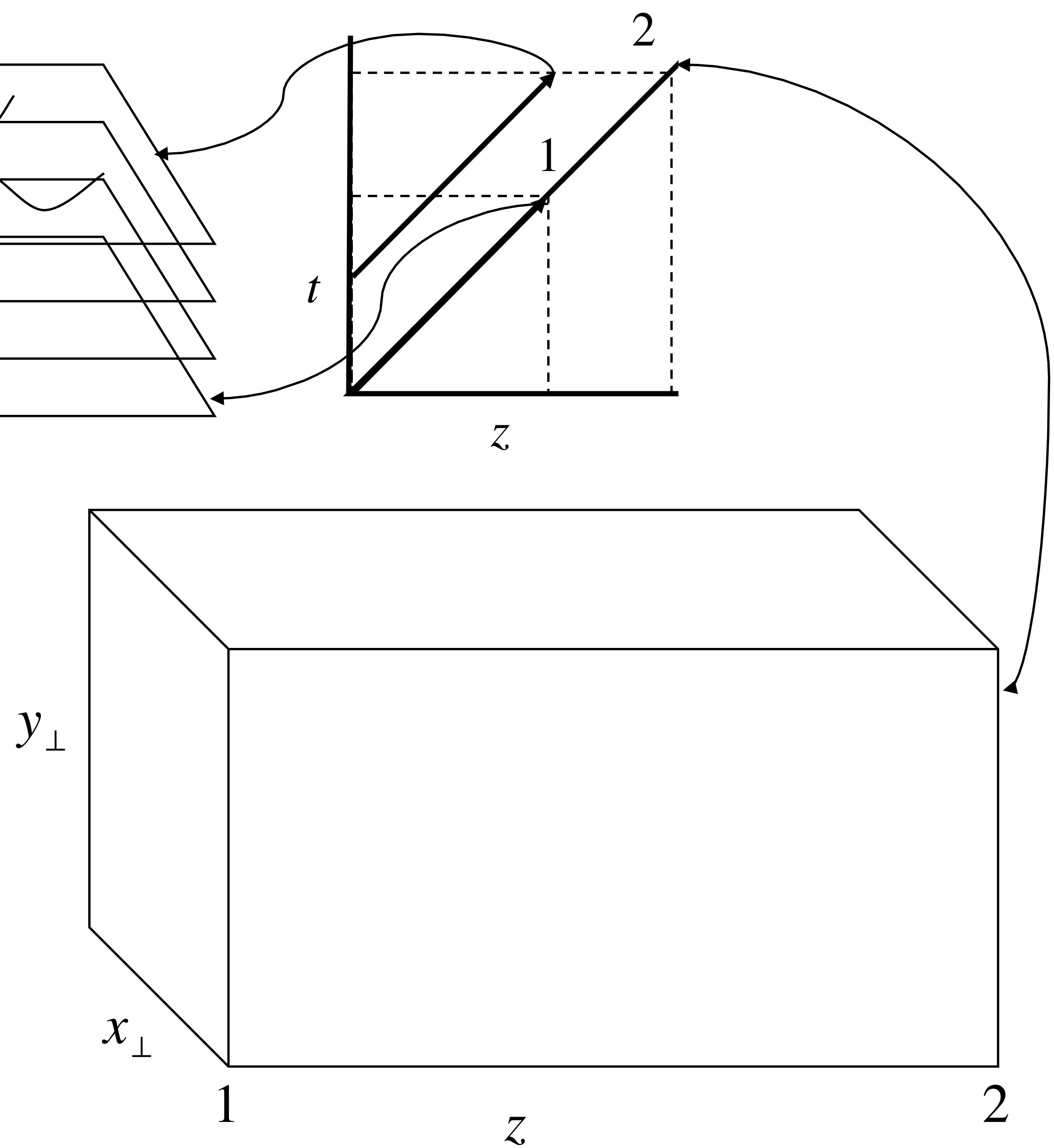
- Unruh (1976): Hawking radiation seen by accelerating observer
- Appears with any event horizon, not just black holes: identify entropy of thermal radiation with missing information
- Jacobson (1995): Einstein equation derived from thermodynamics (~ equation of state)
- Classical GR from 2+1D null surface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



Jacobson: points=2D surfaces

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

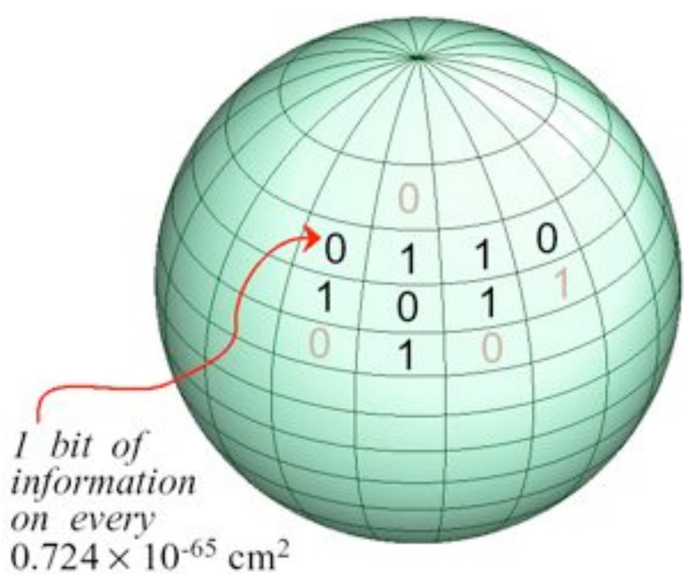
- Strominger, Vafa (1996): count degrees of freedom of extremal higher-dimension black holes using duality
- All degrees of freedom appear accounted for
- Agrees with Hawking/Beckenstein thermodynamic count
- Unitary quantum system (but zero temperature)
- Strong indication of a minimum length ~ Planck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

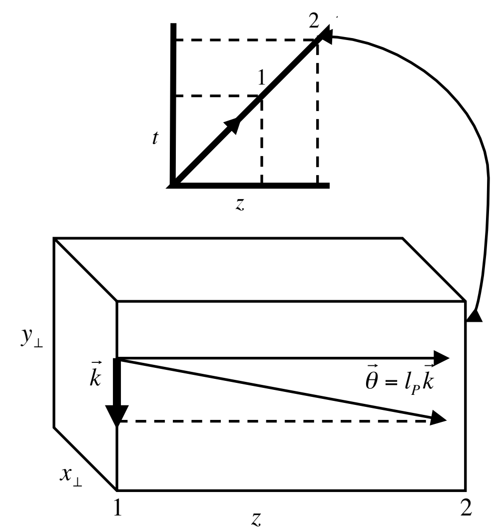
Holography 6: Exact dual theories in N-1 dimensions

- 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

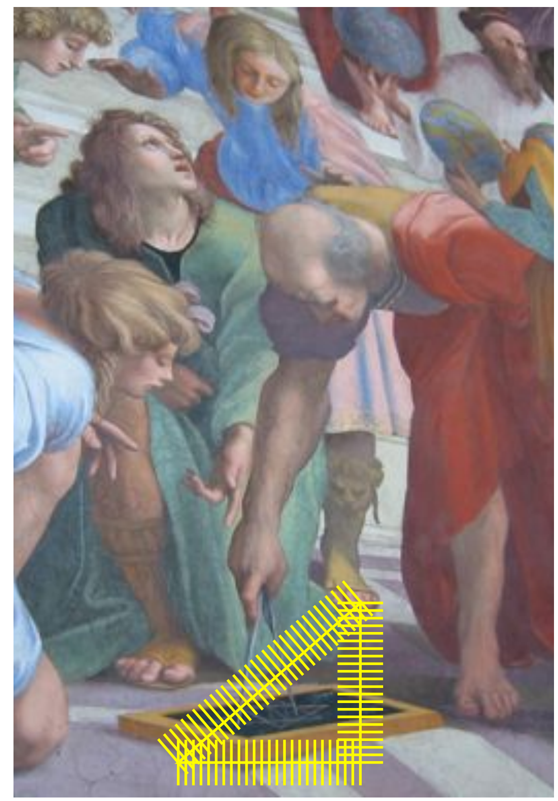
limited information content

What does it look like
"from inside"?

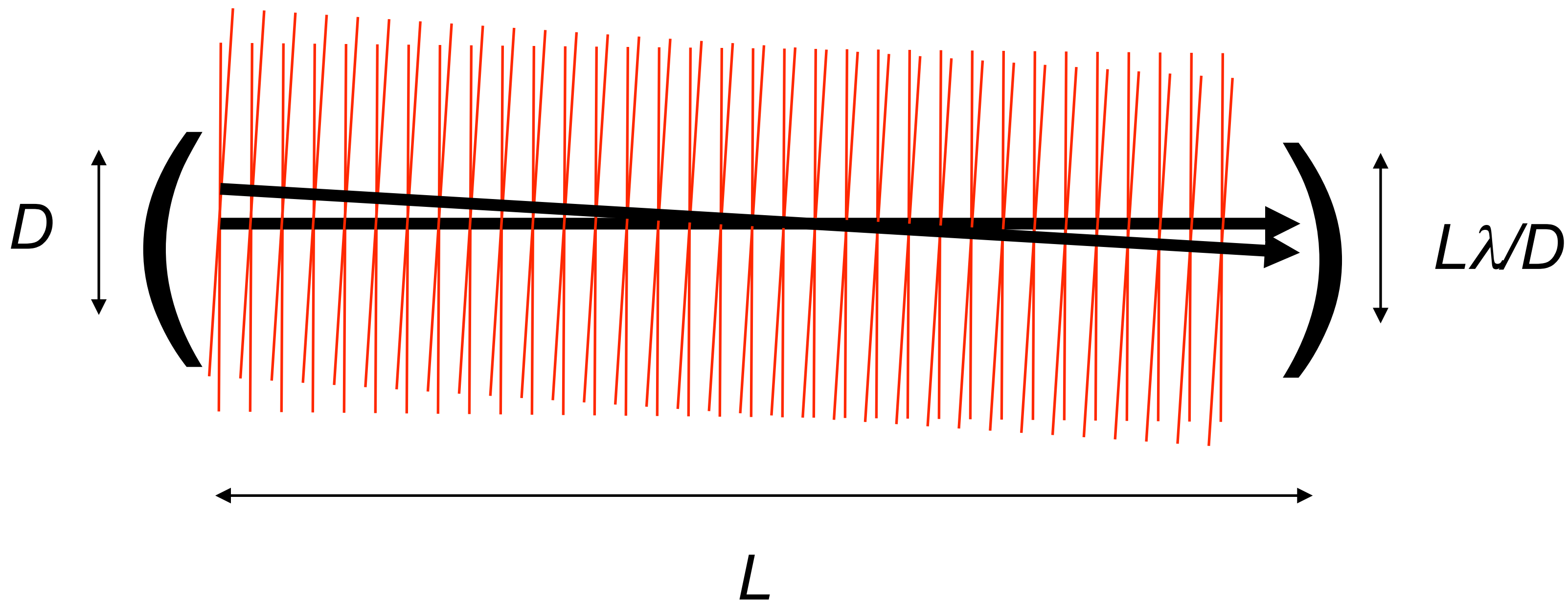
Holographic Quantum Geometry

- 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

$$l_P = \sqrt{\hbar G_N / c^3} = 1.616 \times 10^{-33} \mathrm{cm}$$



Ray limit of wave optics: Rayleigh uncertainty



- Aperture *D*, wavelength λ *:* angular resolution λ/D
- Size of diffraction spot at distance *L: L*λ/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,

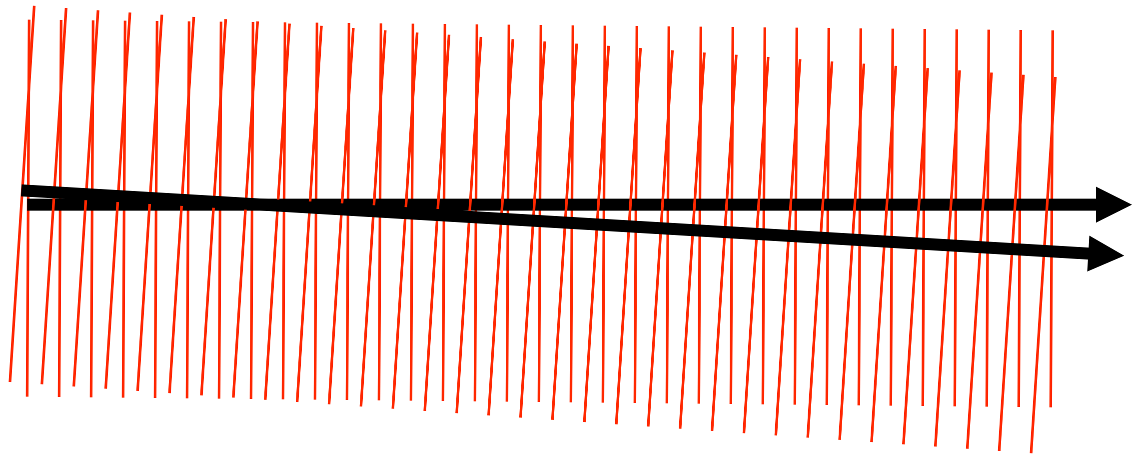
$$D = \sqrt{\lambda L}$$

  is about a millimeter

- This is why even perfect holograms look blurry

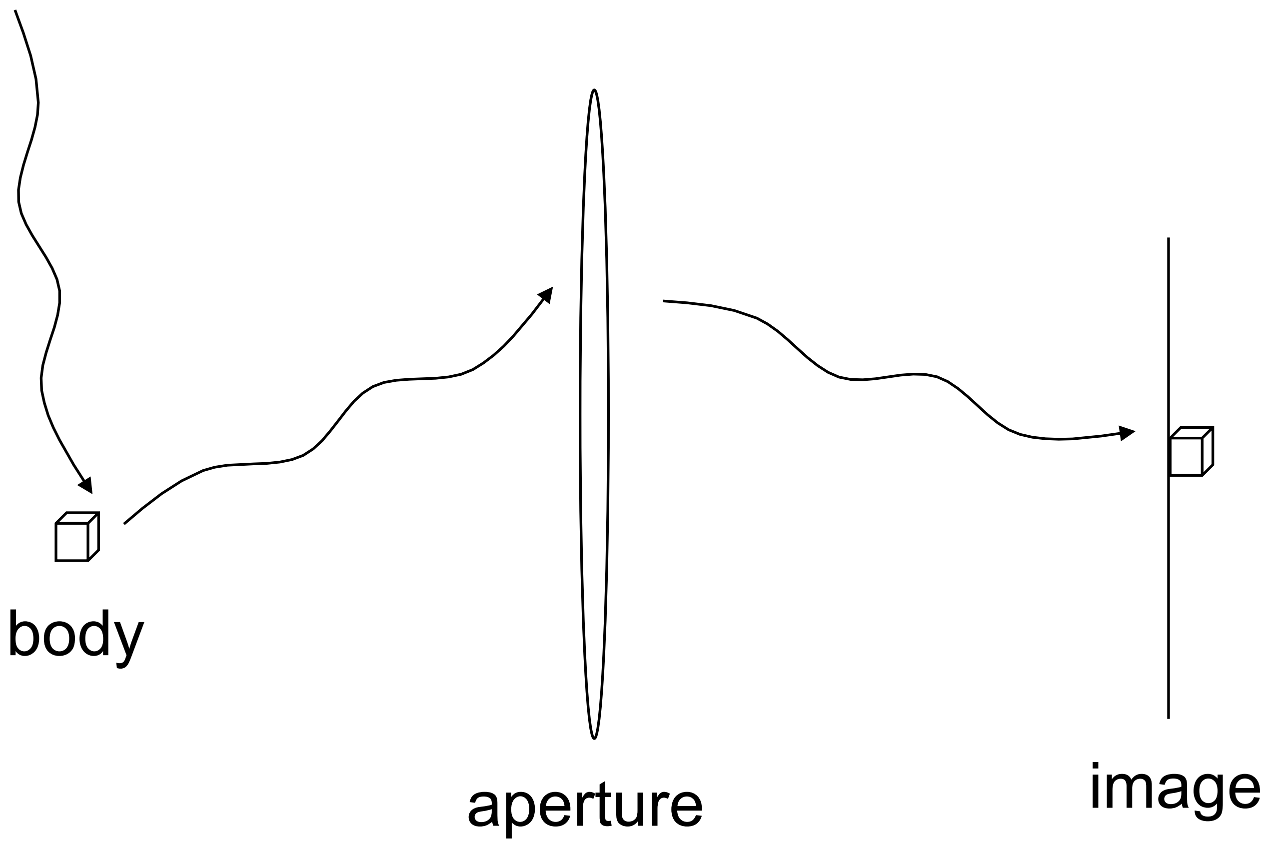
- If you "lived inside" a hologram, you could tell by measuring the blurring

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

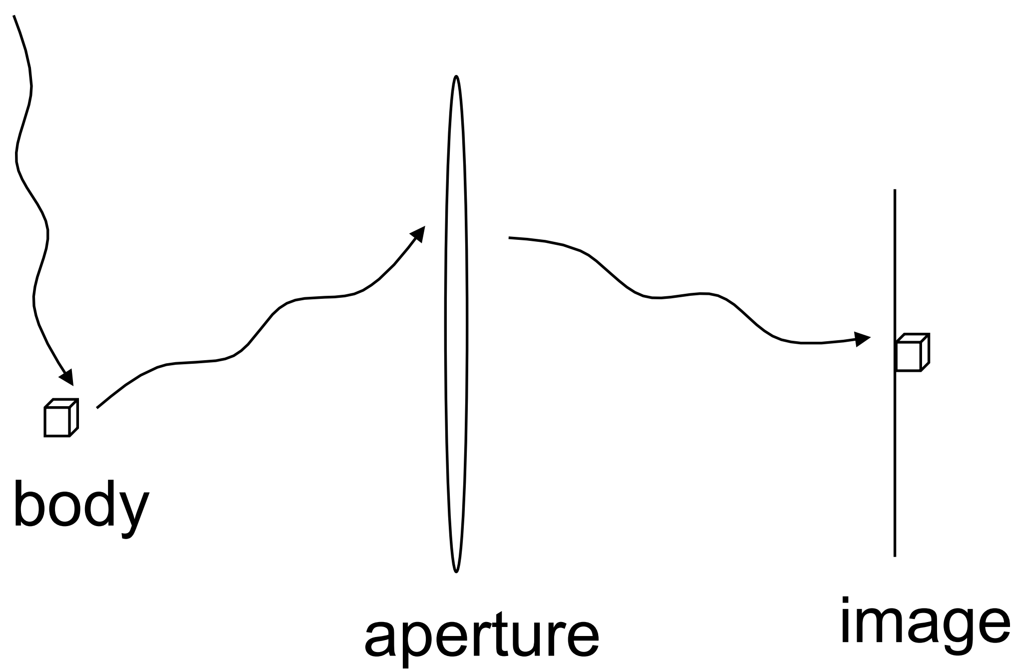
"Heisenberg microscope"



Δ(measured position) x Δ(momentum of perturbation)> hbar/2

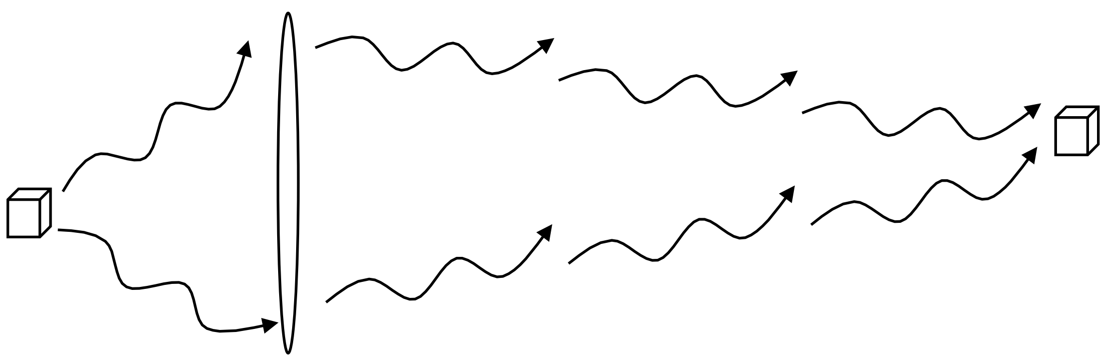
Heisenberg Microscope

- 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
- Δ(measured transverse position of a body) x Δ(momentum of measuring radiation) > hbar/2
- Δ 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
- Δ(position 1) x Δ(position 2) > (Planck length) x (separation/2)
- Δ position ~ optimal "aperture", depends on separation
- Property of (quantum) spacetime geometry: **limiting precision of Planck imaging**
- State of metric depends on measurement

holographic approach to the classical limit

- Angles are indeterminate at the Planck scale, and become better defined at larger separations:

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

- But uncertainty in relative transverse position **increases** at larger separations:

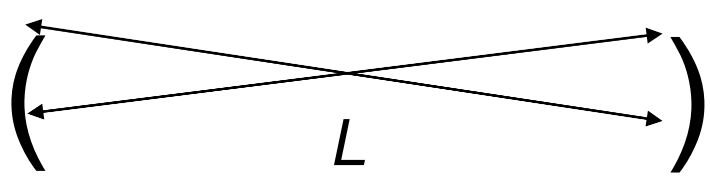
$$\Delta x_\perp^2 > l_P L$$

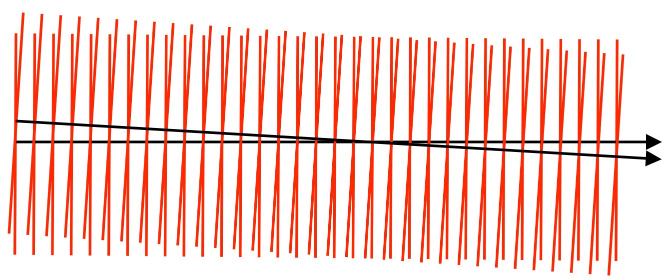
- Not the usual classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

Holographic indeterminacy in angle

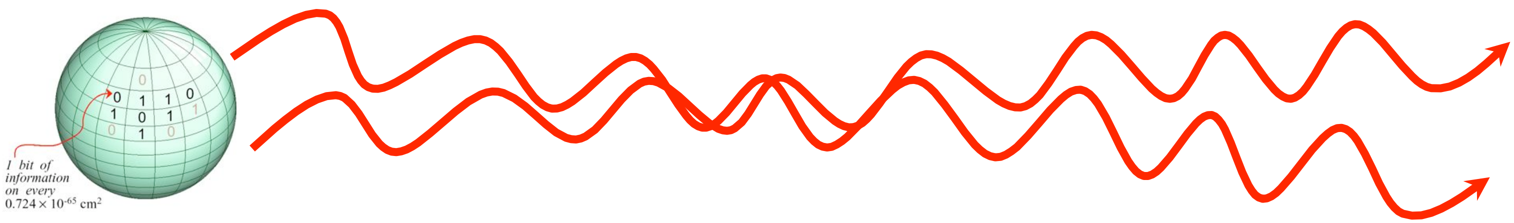
Angular orientation of a null path defined by Planck wavelength particles is uncertain, with standard deviation

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





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:

$$\Delta x_1 \Delta x_2 > l_P L/2$$

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

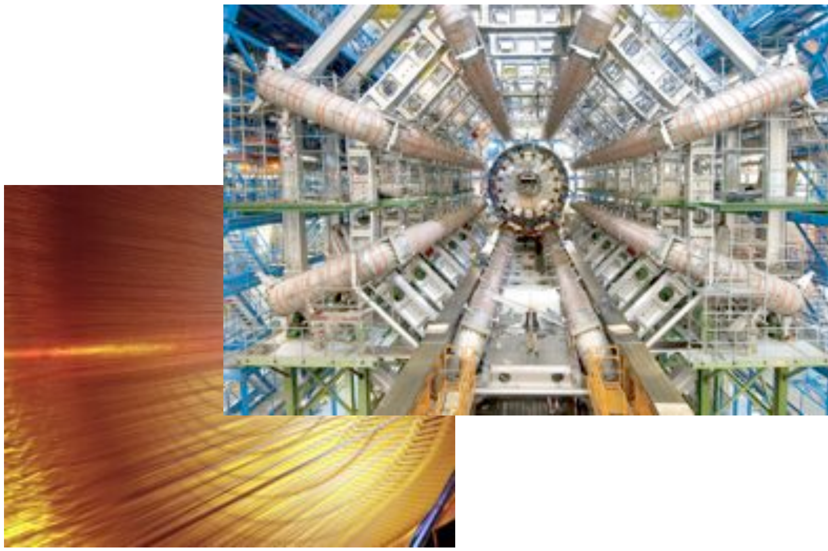
CJH, arXiv: 0706.1999, 0709.0611

Measuring fluctuations in quantum geometry

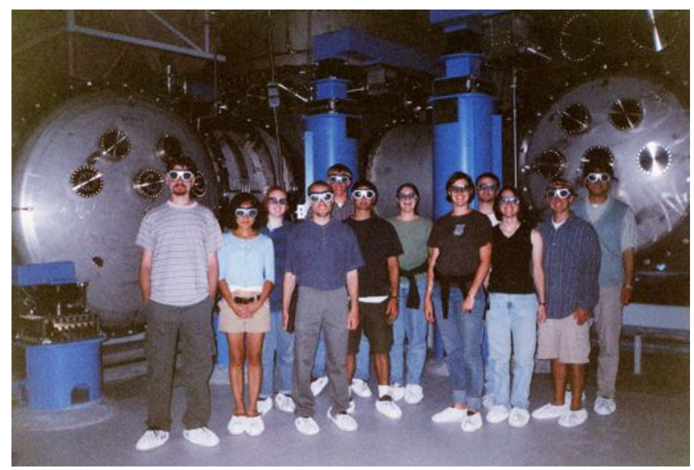
- Distant spacetime is only defined insofar as it can be measured locally using Planck radiation
- Distant events are fuzzy objects, not points
- Endpoints of trajectories (interaction events) are uncertain
- Indeterminacy of worldlines leads to fluctuations in measured quantities

What is the best microscope for measuring quantum geometry?

CERN/FNAL: $\mathrm{TeV}^{-1} \sim 10^{-18}$ m



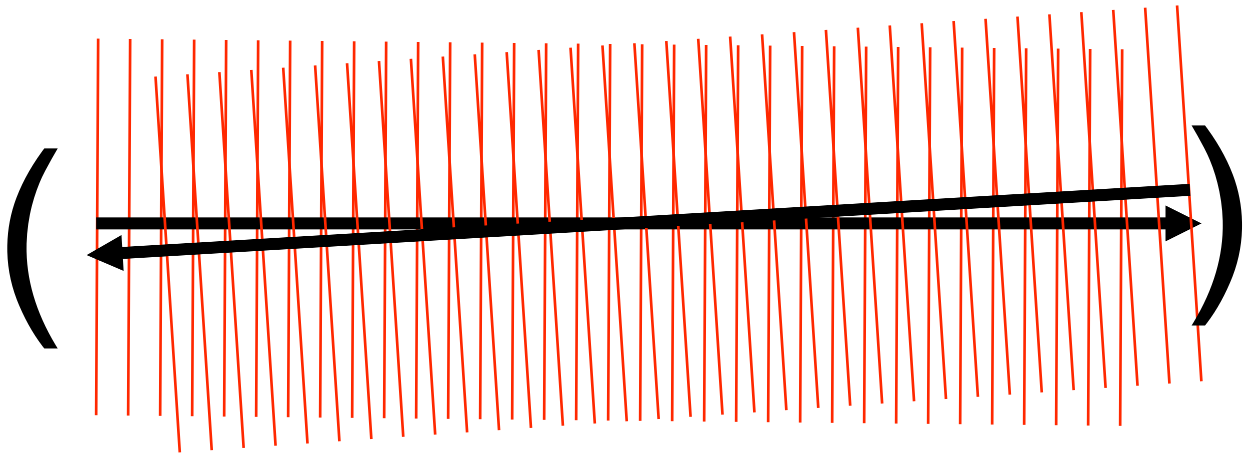
LIGO/GEO: $\sim 10^{-19}$ m
over $\sim 10^{3}$ m baseline



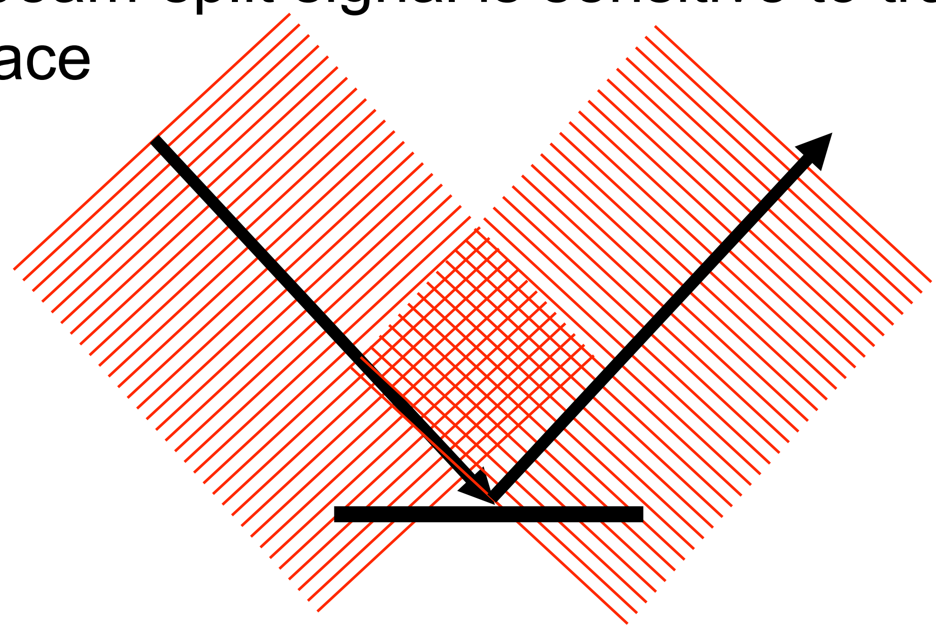
Interferometers as Planck telescopes

- 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

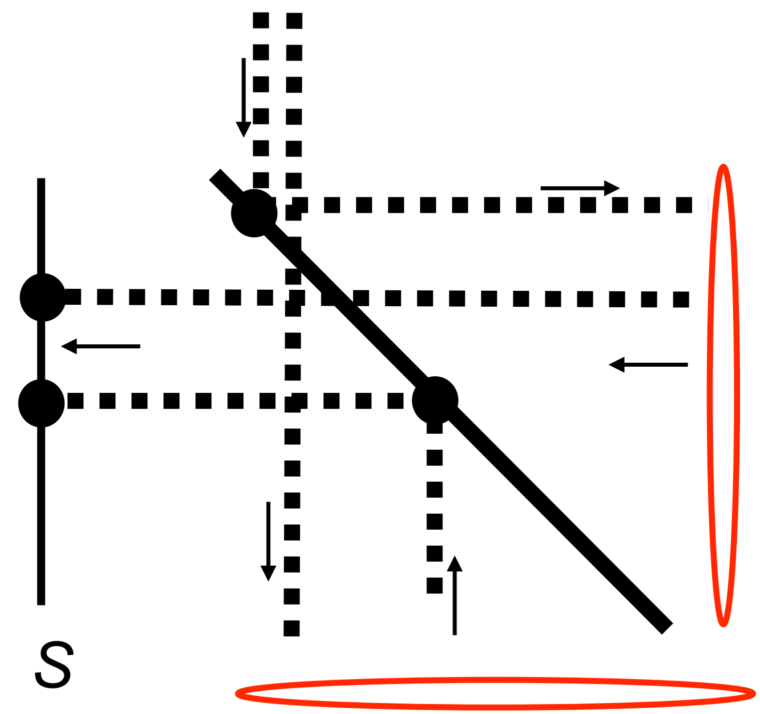


- But phase of beam-split signal is sensitive to transverse position of surface



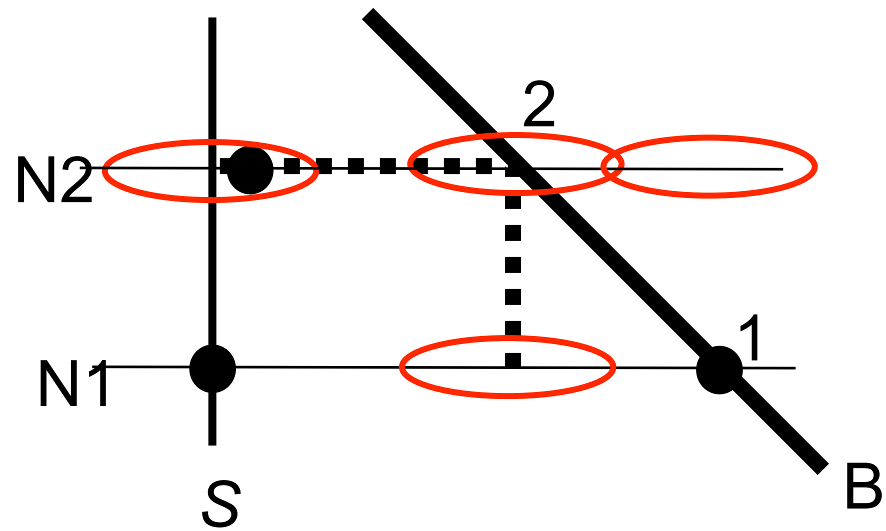
Measurement of transverse position at beamsplitter

- 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



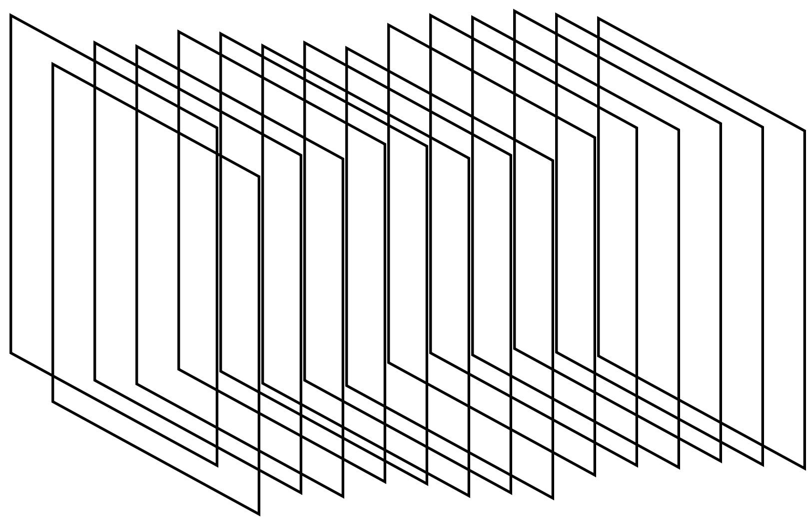
$$\Delta x_1 \Delta x_2 > l_P L/2$$

- 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

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

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 ~ dimensionless metric perturbation

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

~ metric fluctuations with flat power spectral density

$$h_H^2 \simeq L\Delta\theta^2 \approx t_P$$

h_H^2 =mean square perturbation per frequency interval

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

Holographic Noise

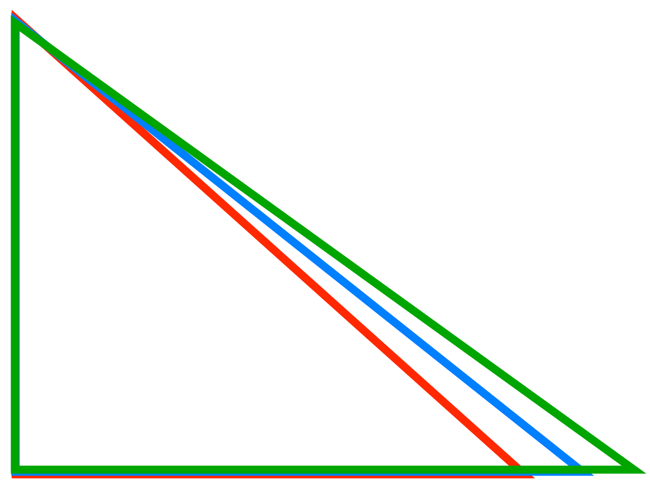
Universal ***holographic noise*** *~ flat power spectral density of metric* ***shear*** *perturbations:*

$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22}\mathrm{Hz}^{-1/2}$$

- 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

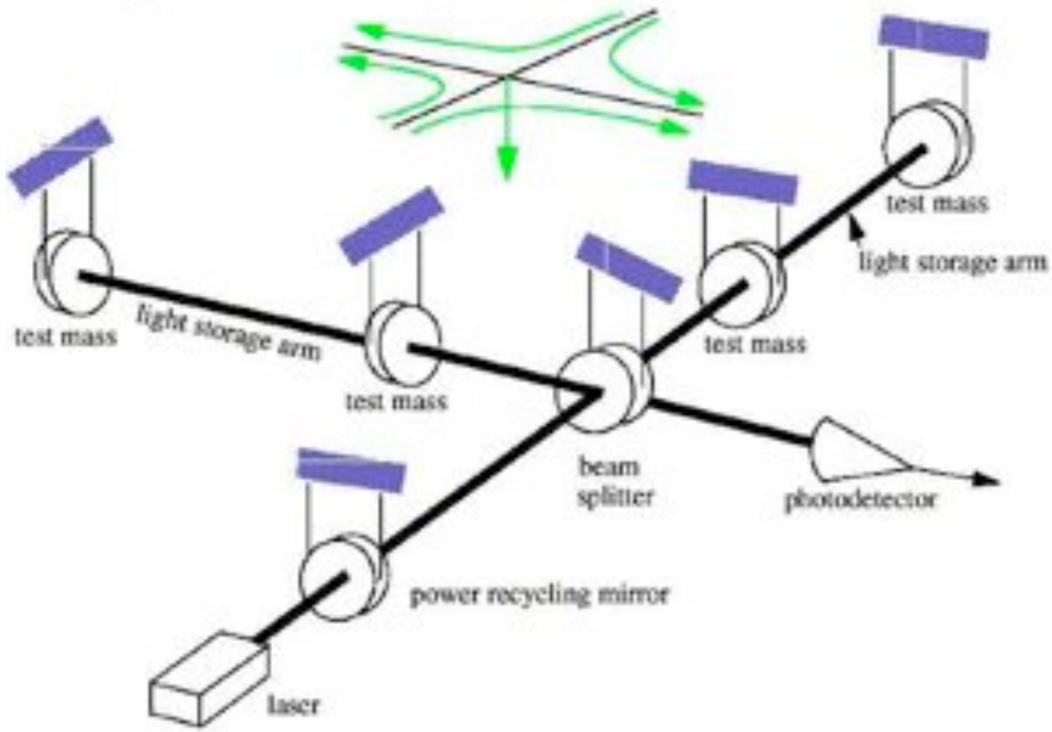
- ~ classical gauge mode
- ~sampling noise rather than thermal noise
- Necessary so the number of distinguishable positions does not exceed holographic bound on Hilbert space dimension
- No curvature
- no strain, just shear
- no detectable effect in a purely radial measurement

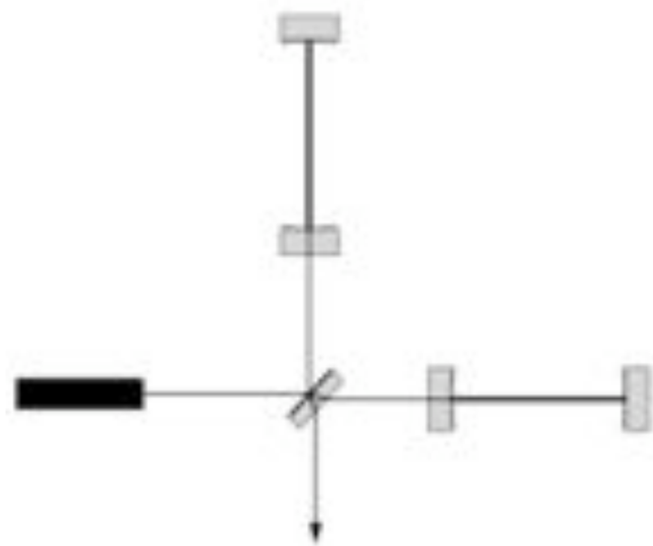


LIGO Hanford Observatory

Schematic layout of LIGO

Fig. 1. Schematic layout of a LIGO interferometer.



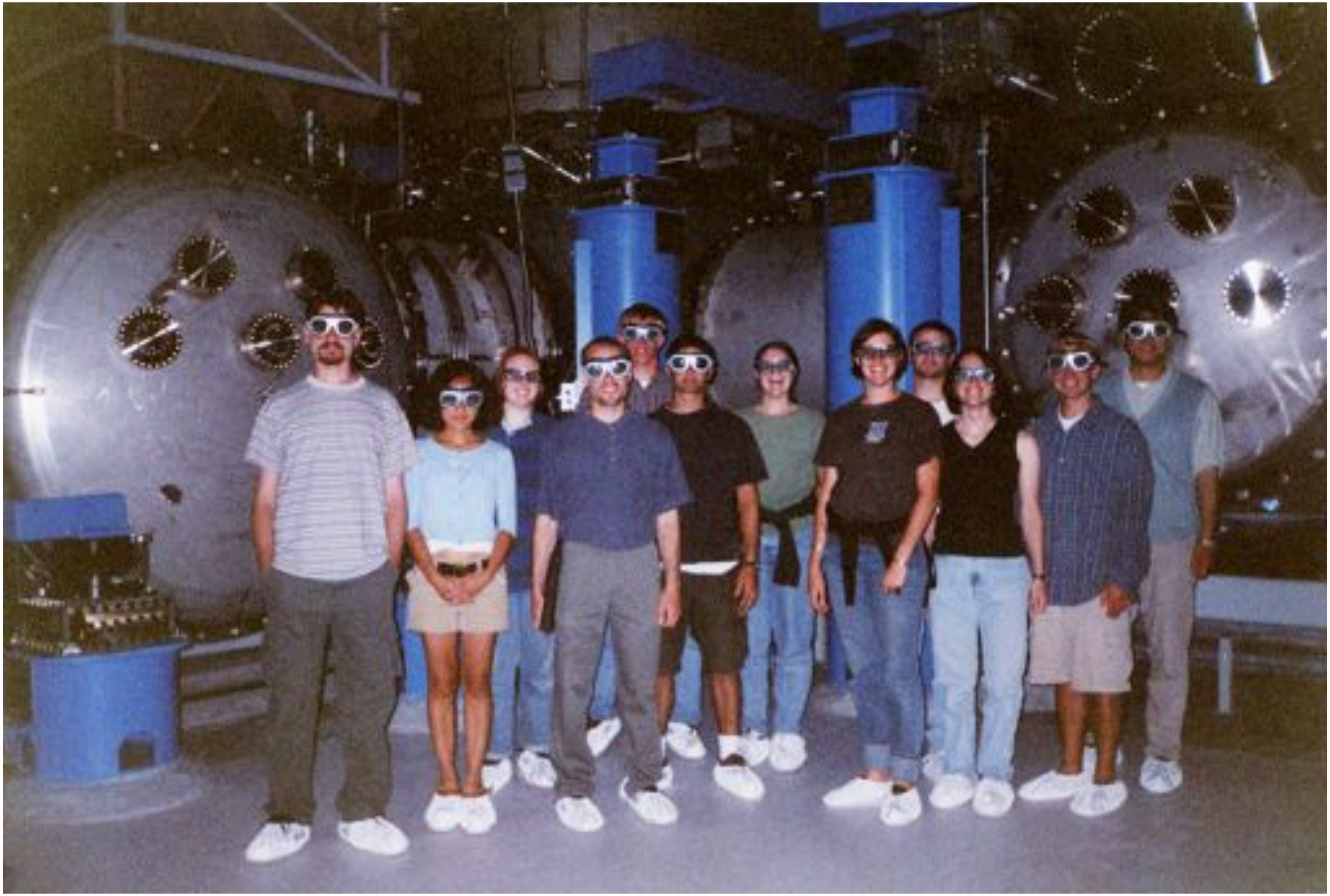


vibration-isolated platform

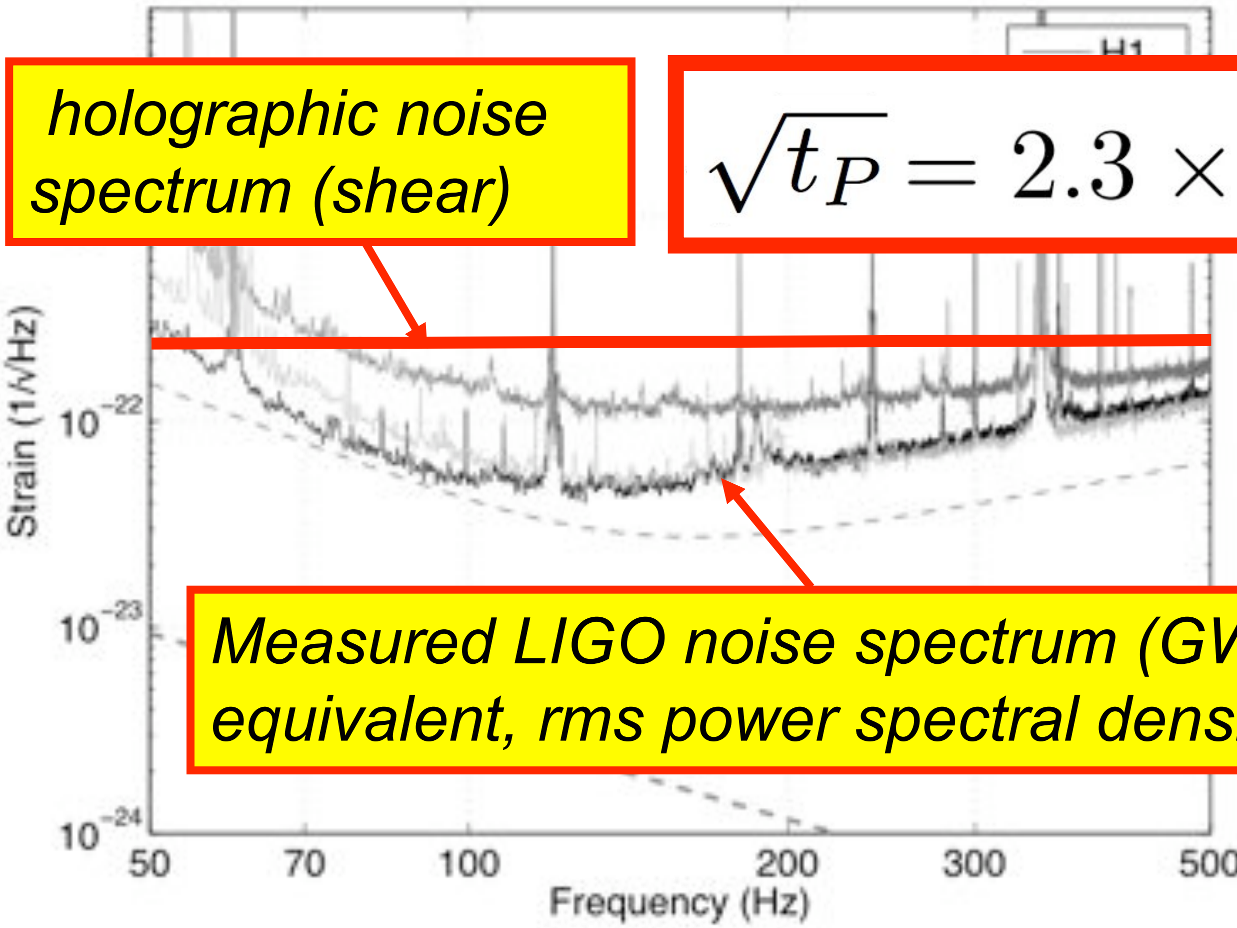
initial alignment

test mass suspended on fine wire

UW Physics undergrads at LIGO Hanford Observatory



LIGO noise (astro-ph/0608606)



holographic noise spectrum (shear)

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

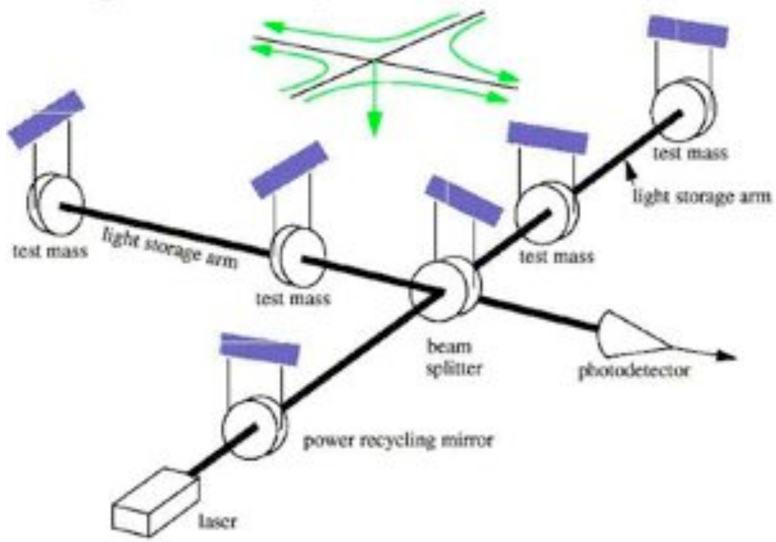
(if shear=strain)

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

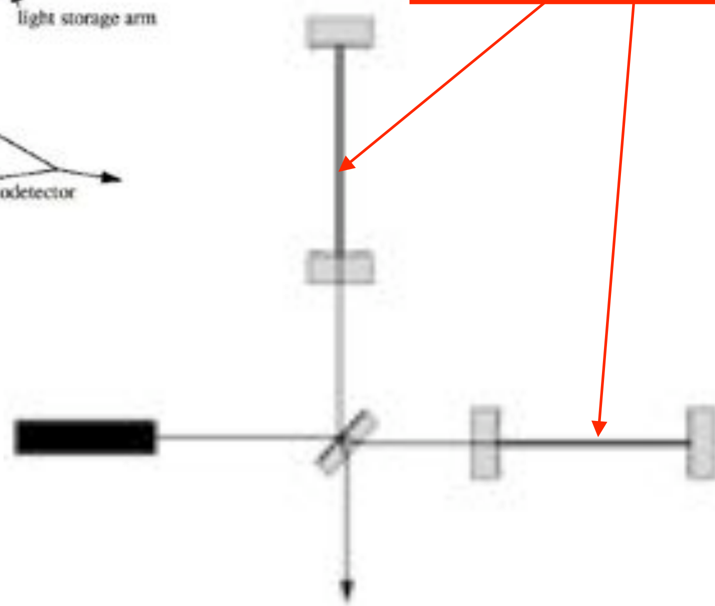
Why doesn't LIGO detect holographic noise?

- 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.

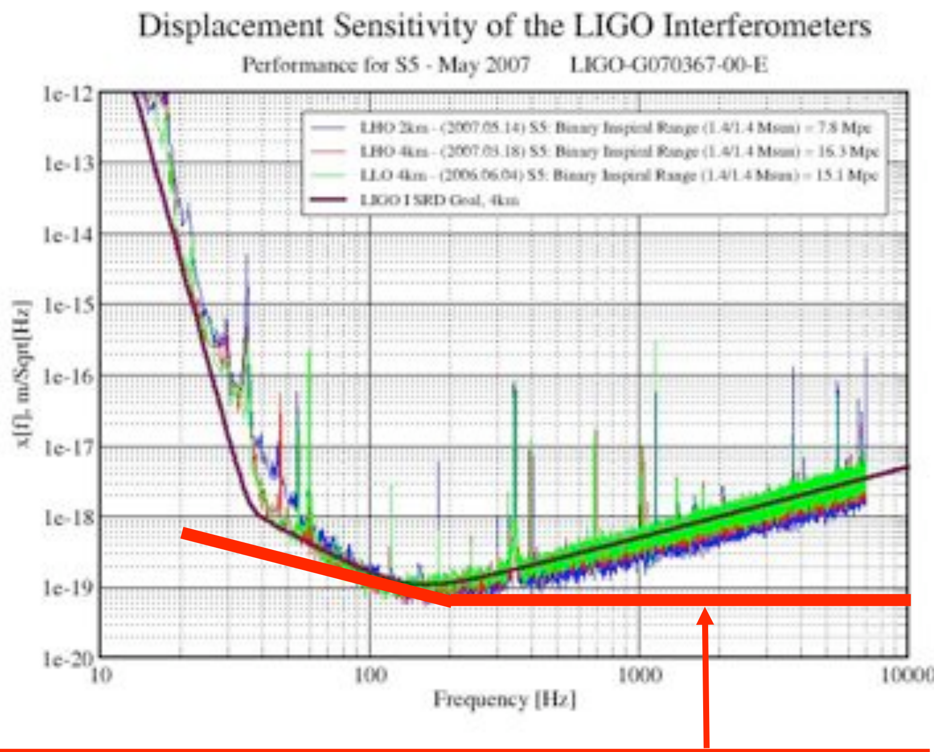


Transverse position measurement is not made in FP cavities



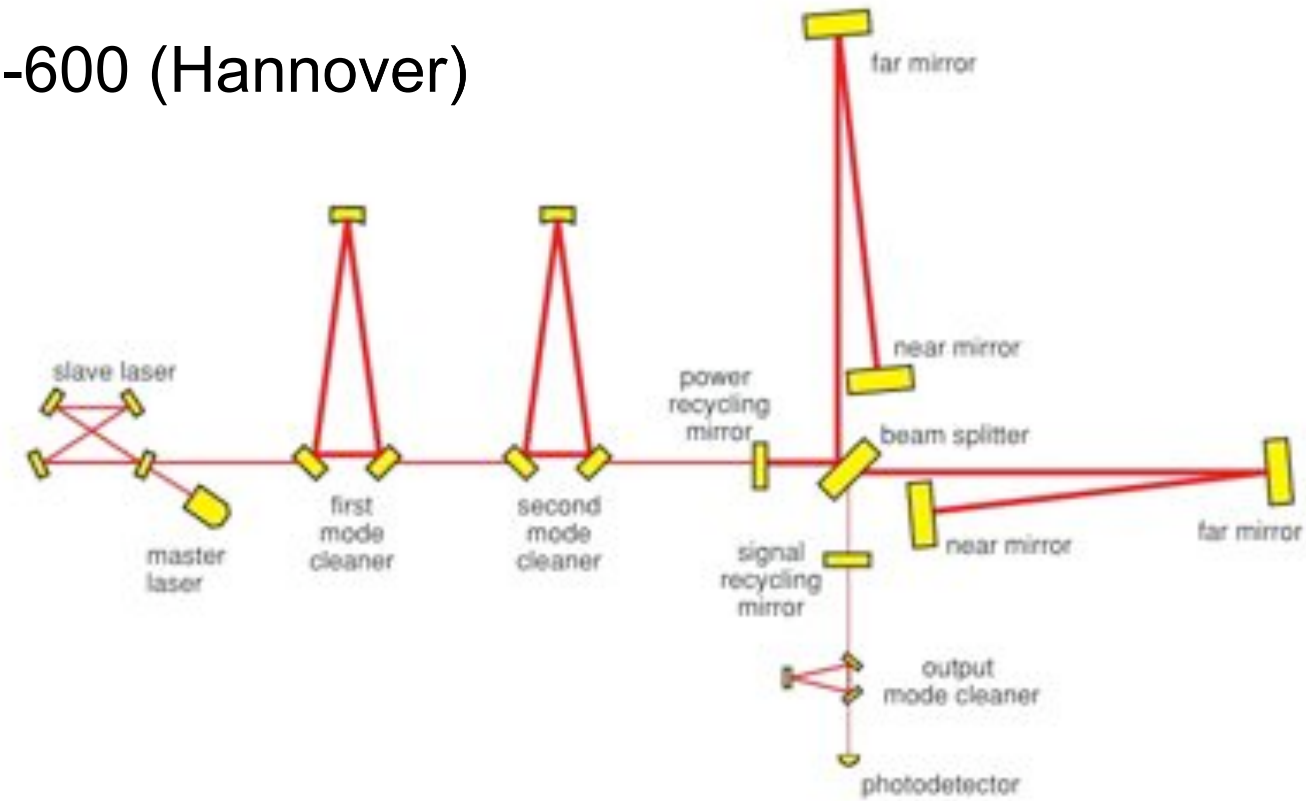
LIGO S5 run: noise in displacement units

- 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

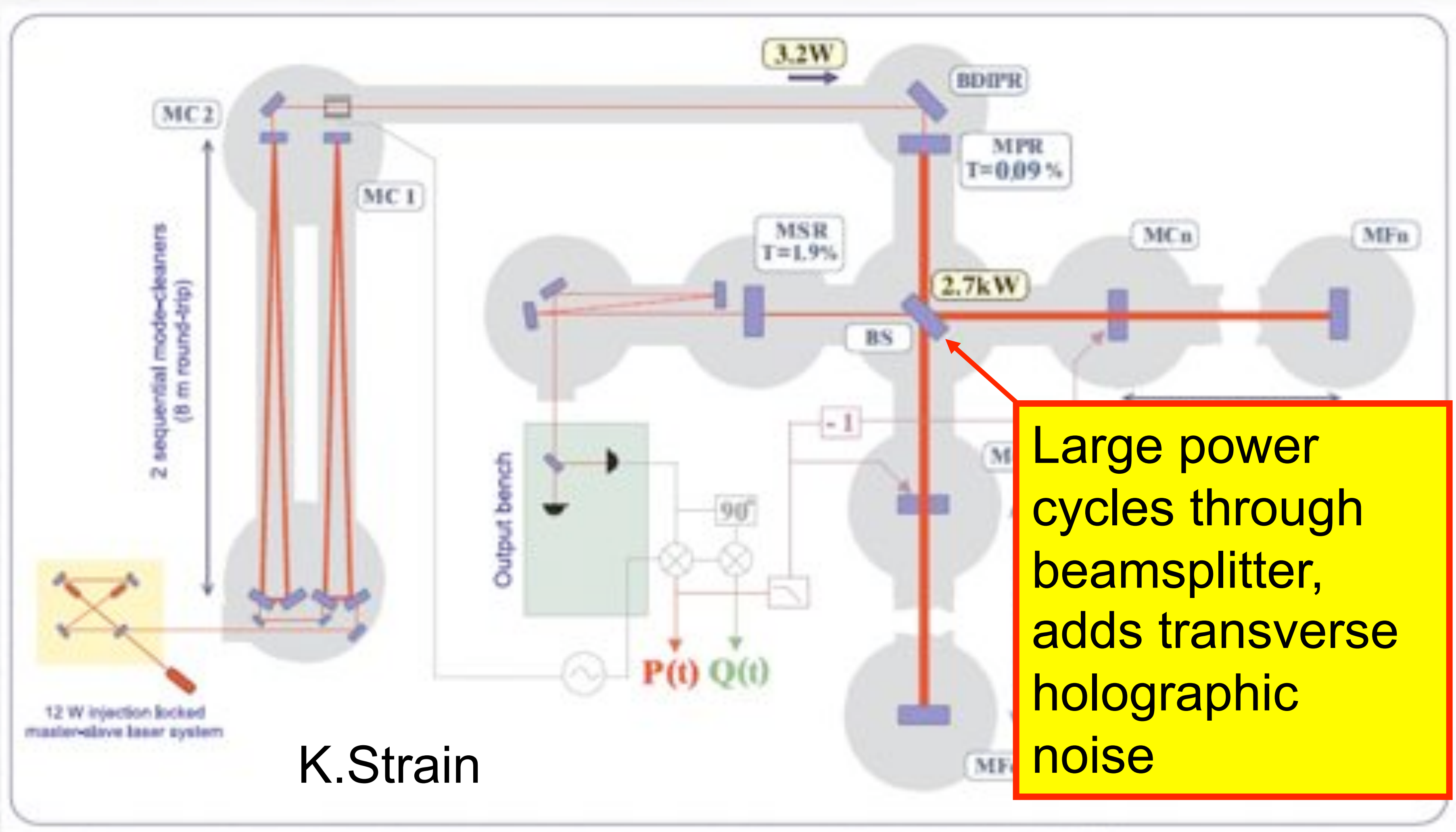


Rough but zero-parameter estimate of holographic noise in LIGO (displacement units)

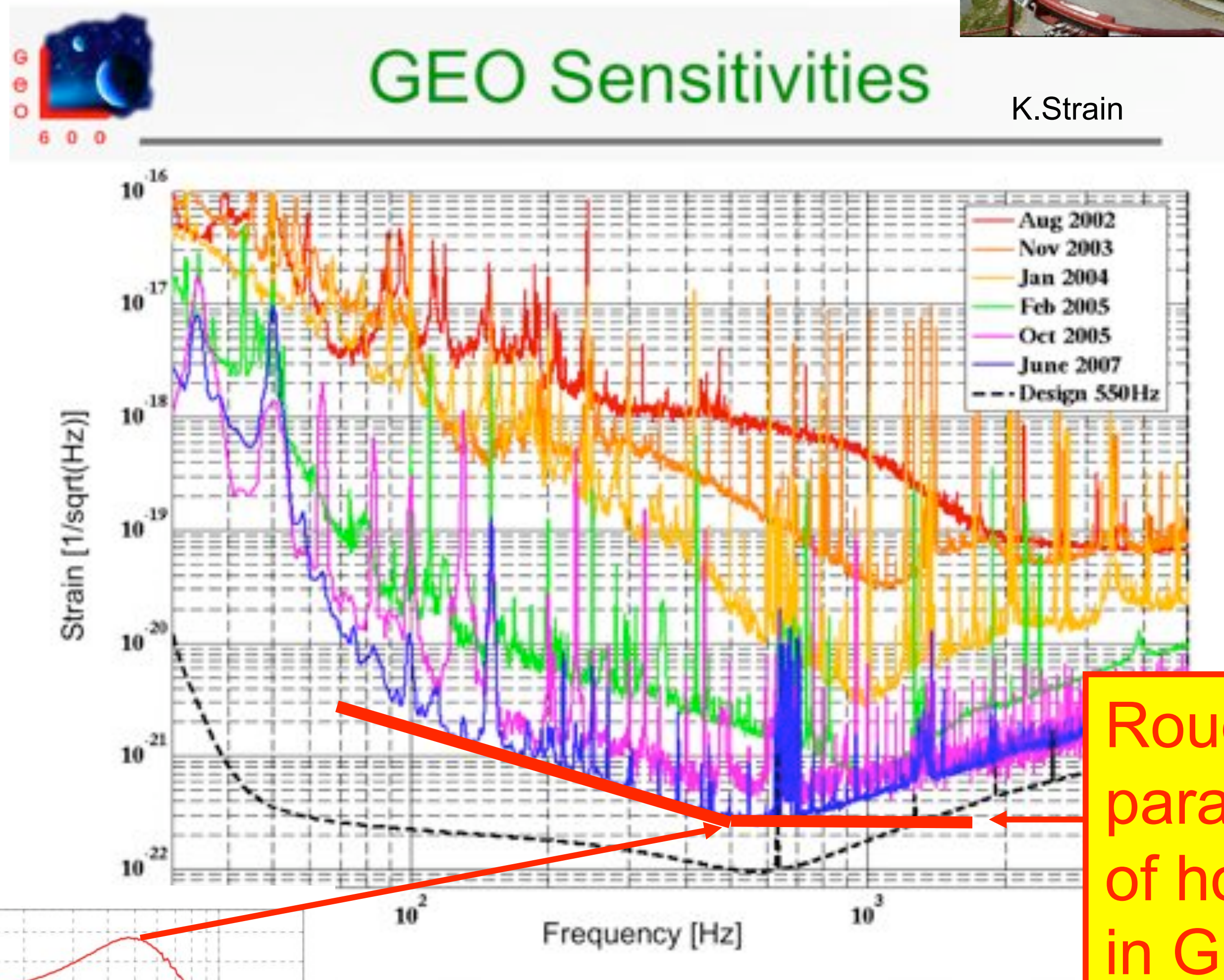
GEO-600 (Hannover)



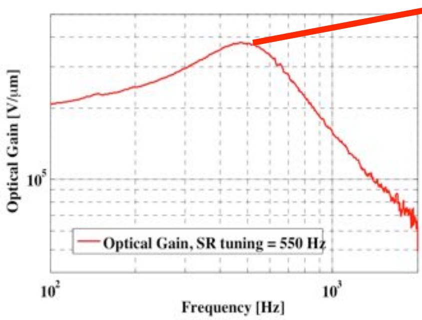
The GEO600 Interferometer



Noise in GEO600



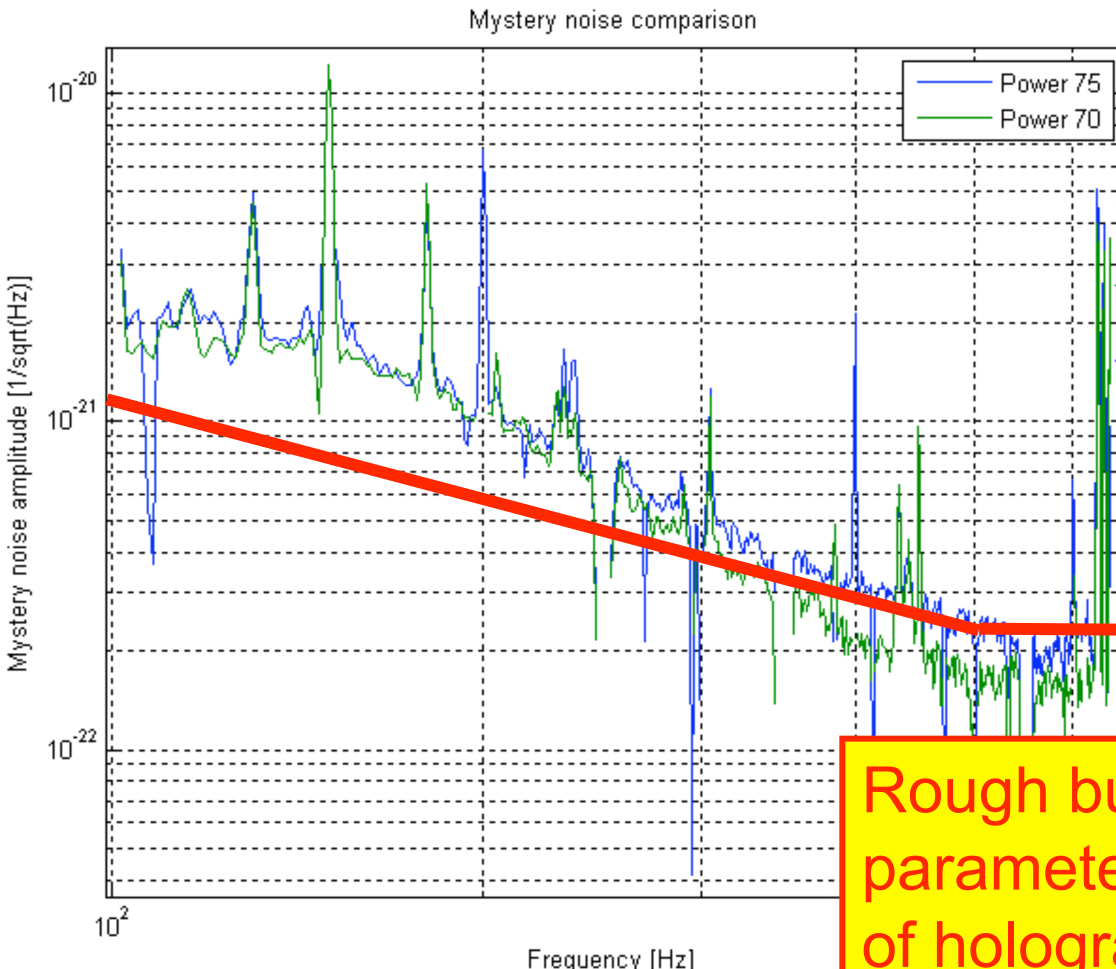
Rough but zero-parameter estimate of holographic noise in GEO600 (equivalent strain)



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

CJH: arXiv:0712.3419

"Mystery Noise" in GEO600



CJH: **arXiv:0712.3419**

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

H. Lück, S. Hild, K. Danzmann

Interferometers can detect quantum fluctuations of geometry

- 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

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!?