Indeterminacy of Quantum Geometry

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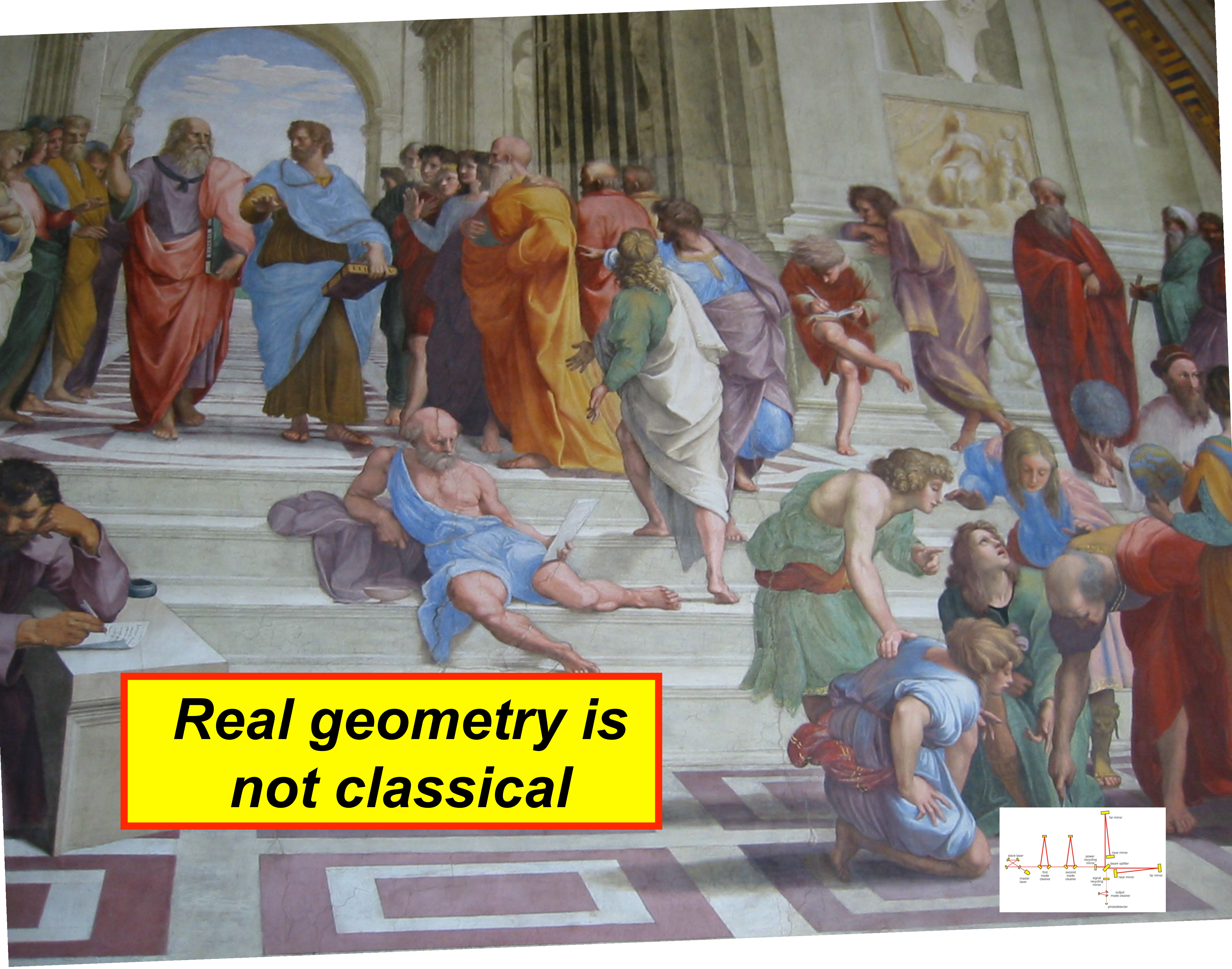


Real geometry is not classical

Quantum Geometry

- Spacetime is a quantum system, not a manifold
- **suppose the Planck wavelength is the smallest length**

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

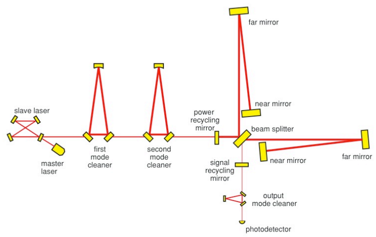
- **Fundamental limit to propagation and measurement of information**
- Leads to transverse fluctuations in geometry much larger than Planck length- and **measurable**

Wave theory of quantum geometry

- Standard quantum field theory: geometry is classical, fields are quantized, modes are independent, "all physics is local"
- Gravitation theory suggests holographic quantum geometry: UV cutoff at the Planck length, 3D states and correlations are spatially nonlocal
- New holographic phenomenology: **relative spacetime positions of events are indeterminate, defined to precision of information propagation and measurement allowed by capacity of Planck wavelength radiation**
- spacetime events and paths complementary to Planck wavelength radiation (classical event~ particle, path~ray)
- Theory of spacetime indeterminacy based on wave optics: wavefunctions represent event positions

Direct measurement of quantum geometry fluctuations

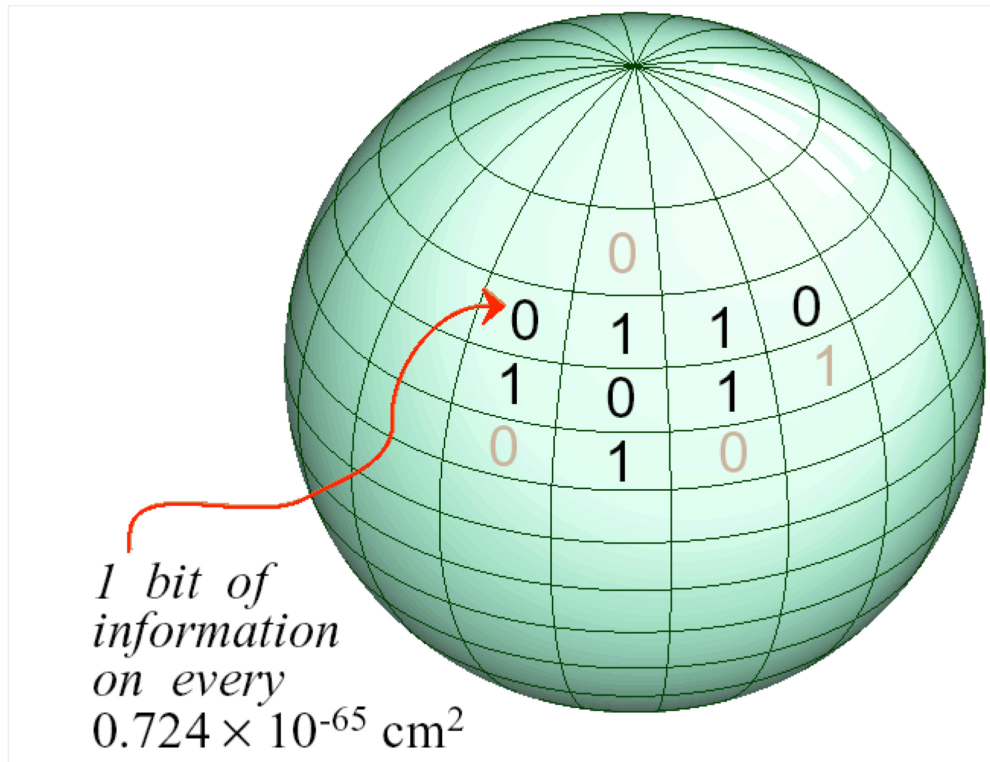
- Experimental approach to small lengths/large energies has been the high energy frontier-- accelerators
- Better macroscopic position measurements by interferometers designed for gravitational wave detection (narrow wavefunction of macroscopic mass position: small Heisenberg uncertainty)
- Quantum wave geometry predicts a new 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
- CJH: **arXiv:0806.0665**, also PRD D 77, 104031 (2008)



"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

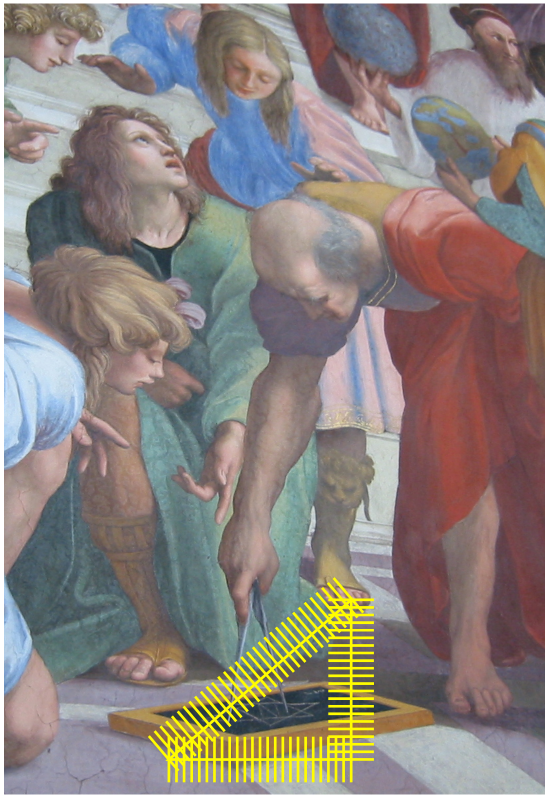
A holographic world is blurry

limited information content

What does it look like
"from inside"?
("Flatland" realized with
waves)

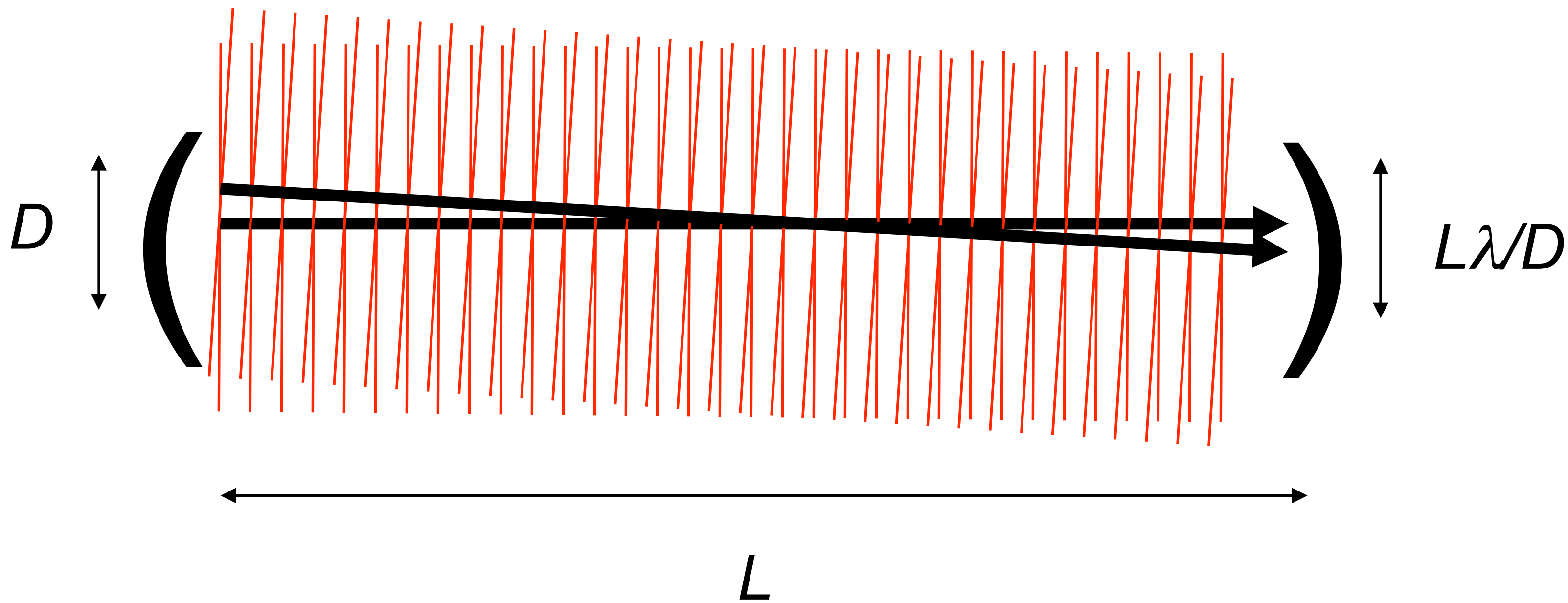
Holographic Quantum Geometry

- Spacetime is a quantum system
- **Conjecture: the world is formed by Planck wavelength null waves**
- "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,

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

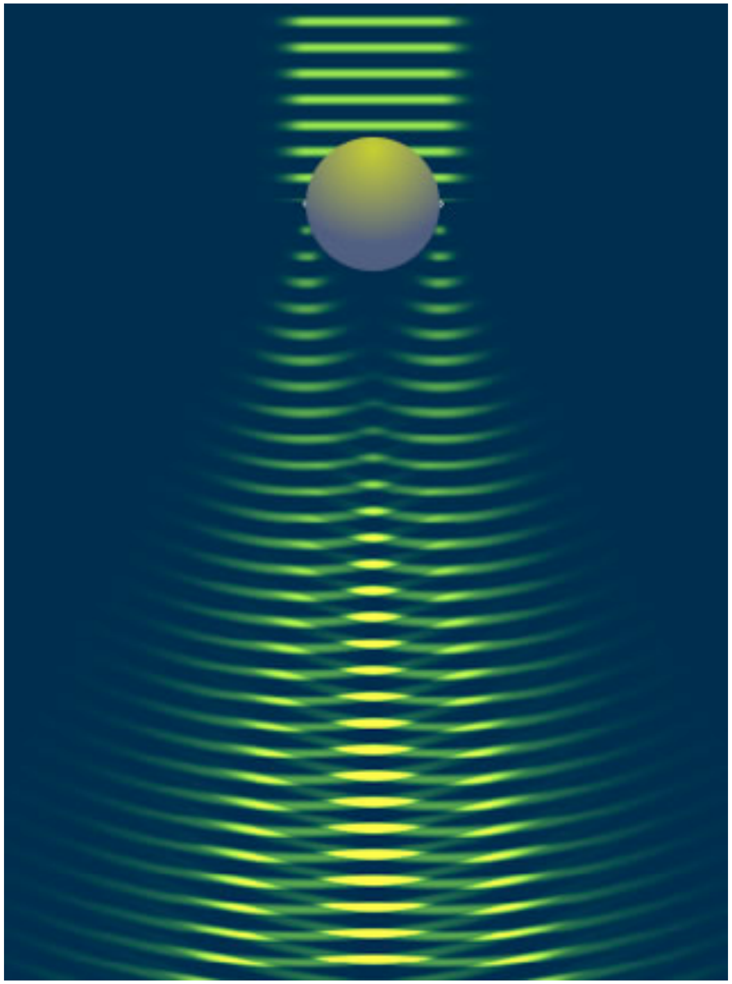
is about a millimeter

- Larger aperture gives sharper image but then photon paths and arrival positions cannot be measured so well

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

Wave Theory of Spacetime Indeterminacy

- Adapt van Cittert-Zernike theory of transverse correlation in wave optics
- theory of “fuzzy event positions”
- Complex amplitude=wavefunction
- Complex correlation=quantum correlation
- Intensity=probability
- Set wavelength to match holographic degrees of freedom



Uncertainty of transverse position

Spacetime events are not points but wavefunctions*.* *Transverse to a null trajectory at separation L events are Fourier transforms of each other and have standard deviations of transverse position related by:*

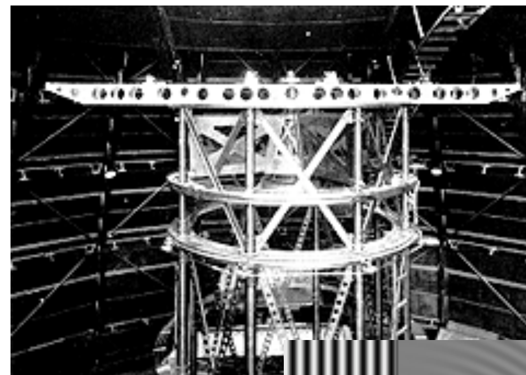
$$\sigma'\sigma = \lambda L$$

For macroscopic L the "uncertainty" is much larger than the wavelength

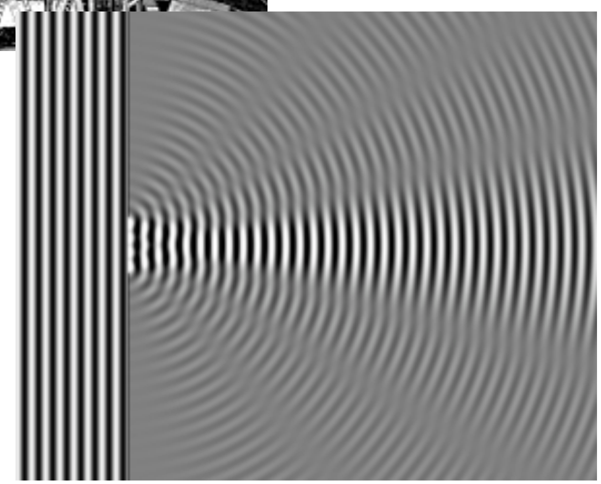
Controlled covariant theory based on wave optics: CJH, arXiv: **0806.0665**

Familiar examples from the world of optics

- Hanbury Brown-Twiss interferometry: correlation of intensity from distant star in widely separated apertures



- Michelson stellar interferometer: fringes from star



- Diffraction in the lab: shadow of plane wave cast by edge or aperture

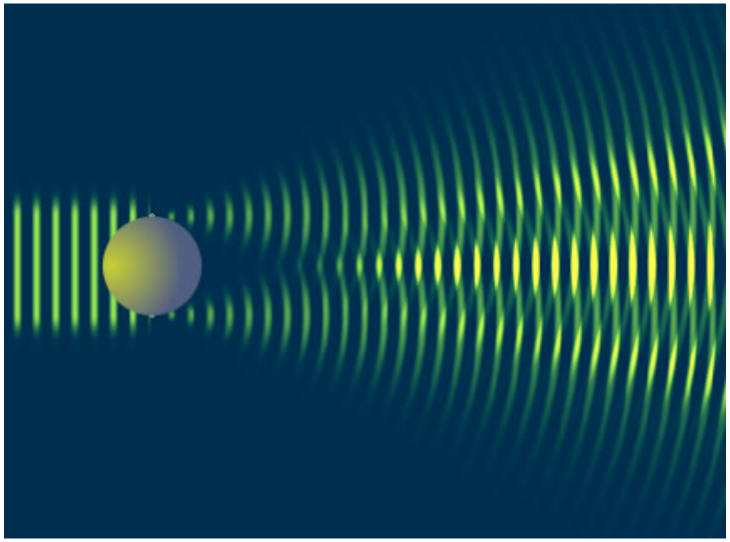
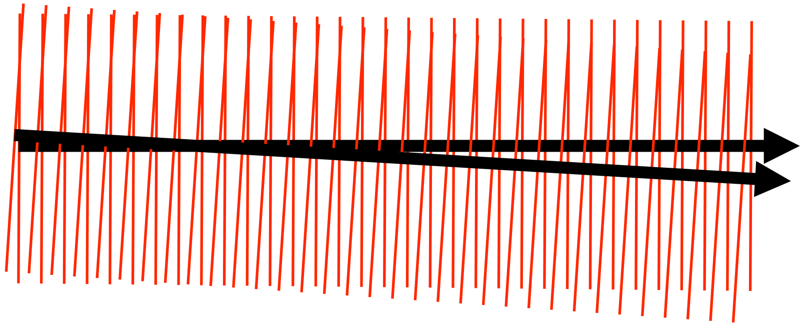
All display similar optical examples of wave phenomena much larger than the waves,

$$\sigma' \sigma = \lambda L$$

Set fundamental wavelength= Planck length

- Agrees with degrees of freedom, minimum wavelength from gravitation theory
- black hole evaporation, unitary behavior of gravitational systems
- Sets absolute normalization with no parameters
- No gravity: flat wavefronts, flat space

Indeterminacy of a Planckian path: diffraction limit of "Planck wavelength telescope"

- spacetime metric defined by paths between events
- Complementarity: path~ ray approximation to waves
- Events on worldline ~ particle interactions with Planck wavelength radiation
- Transverse wavefunction of events displays indeterminacy formally identical to optical wave correlations
- Indeterminacy of geometry reflects limited information content of wave model

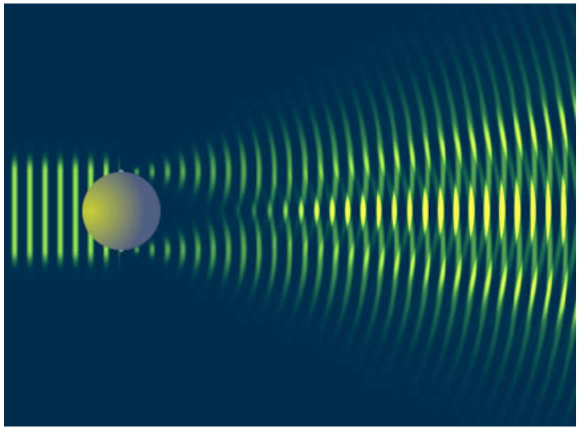
holographic approach to the classical limit

- 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:

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



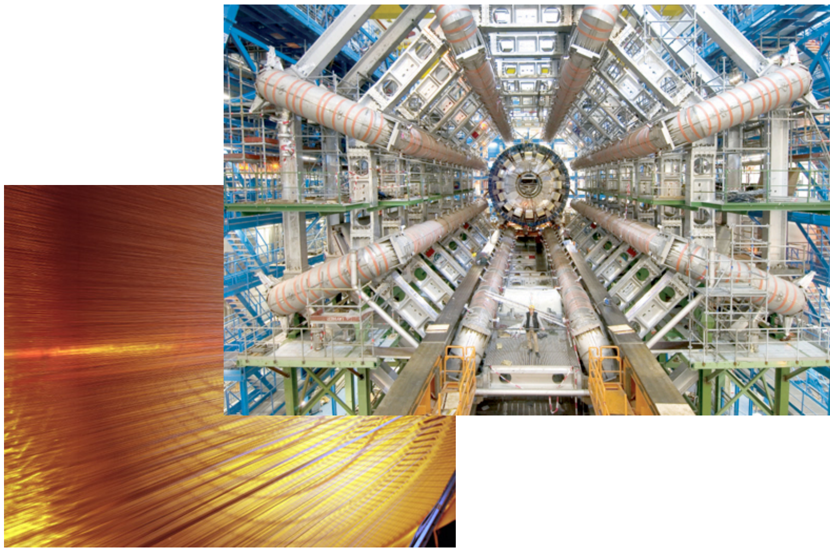
- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

Fluctuations in quantum geometry

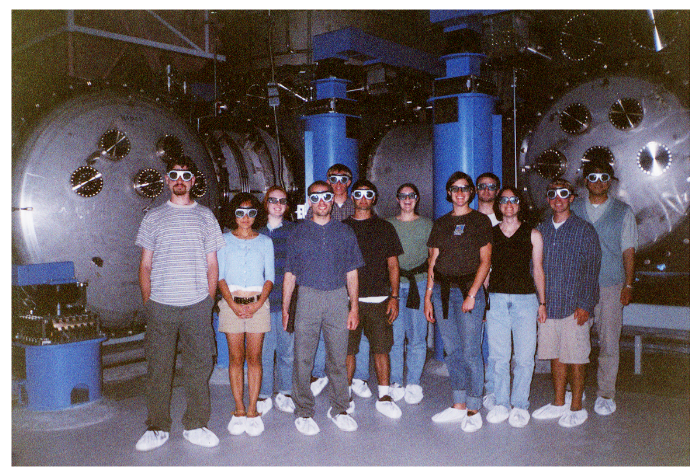
- Distant spacetime is only defined insofar as it can be measured locally using Planck radiation
- Distant events are fuzzy objects, not points
- Endpoints of trajectories (interaction events) are uncertain
- Indeterminacy of worldlines leads to fluctuations in measured quantities
- Statistical predictions not sensitive to model details: direct measure of fundamental information bounds

What is the best microscope for measuring quantum geometry?

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



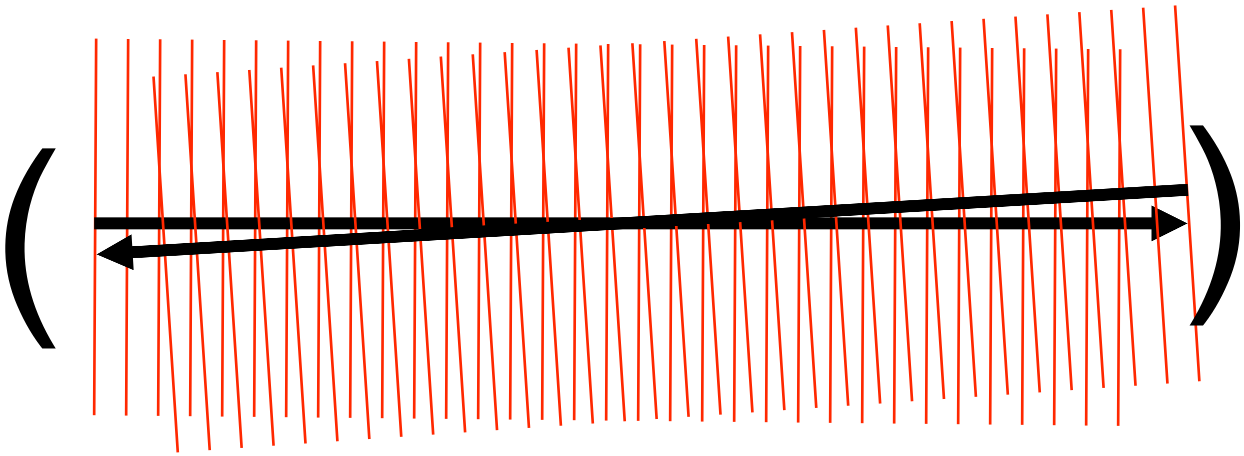
LIGO/GEO: $\sim 10^{-19}$ m
over $\sim 10^{3}$ m baseline



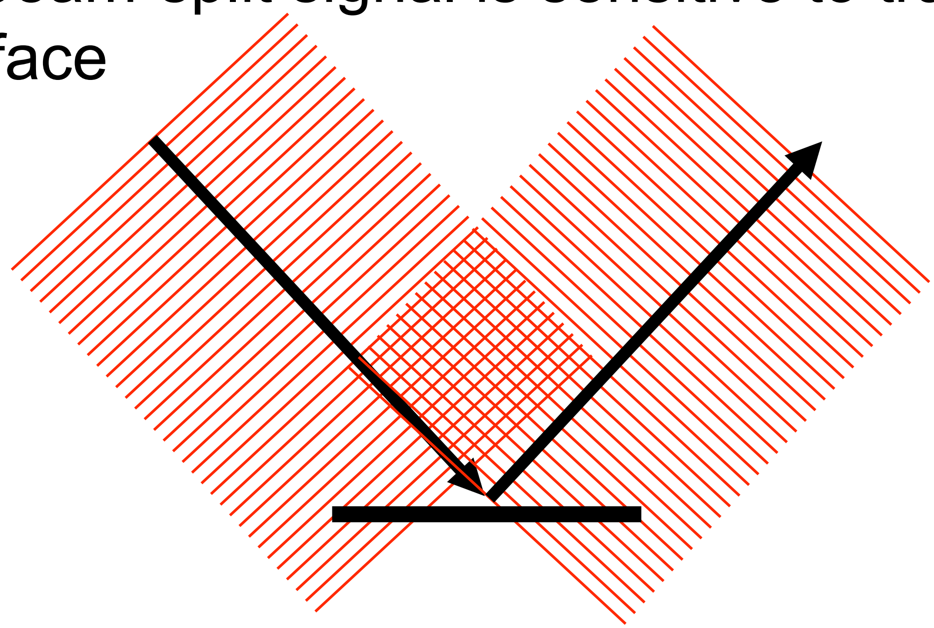
Interferometers as Planck telescopes

- Nonlocality: precise relative positions at km scales
- Fractional precision: angle < 10^{-20}, > "halfway to Planck"
- Transverse position measured in some configurations
- Precision: like two collisions at LHC localized at exactly the same place after a complete circuit
- Proof masses have narrow position wavefunction, measure spacetime wavefunction
- Detect holographic blurring: noise in signal stream

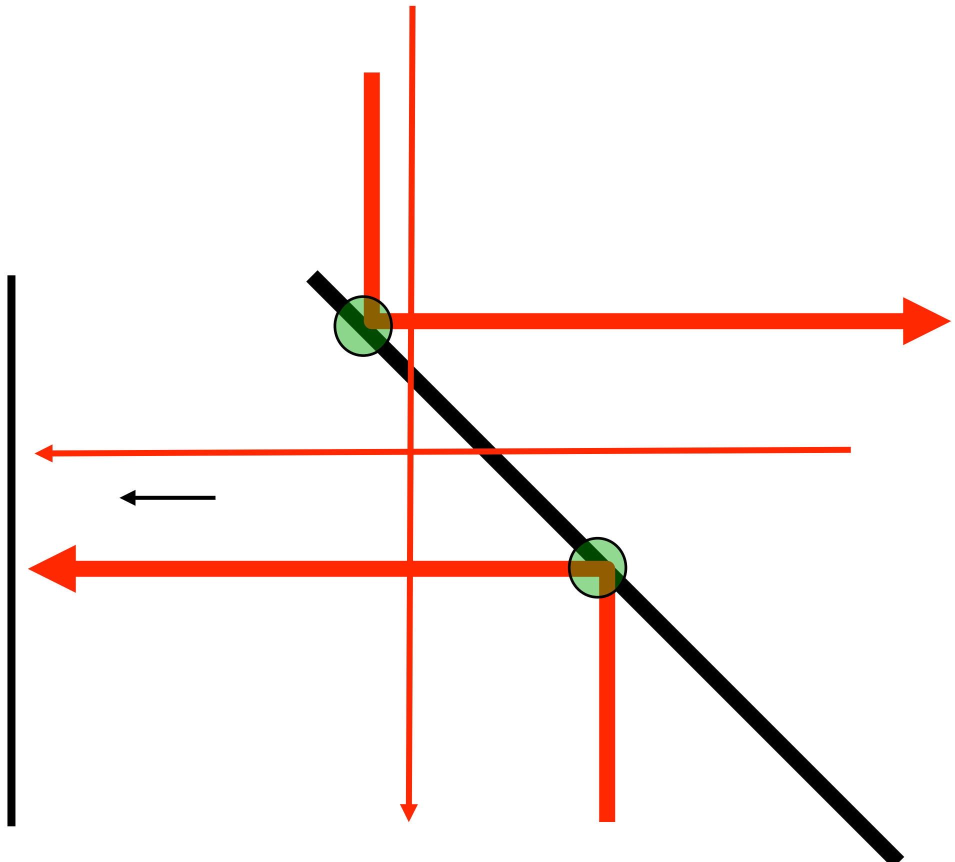
Normal incidence optics: phase signal does not record the transverse position of a surface



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



Beamsplitter and signal in Michelson interferometer



Signal: random phase difference of reflection events from indeterminate position difference of beamsplitter at the two events

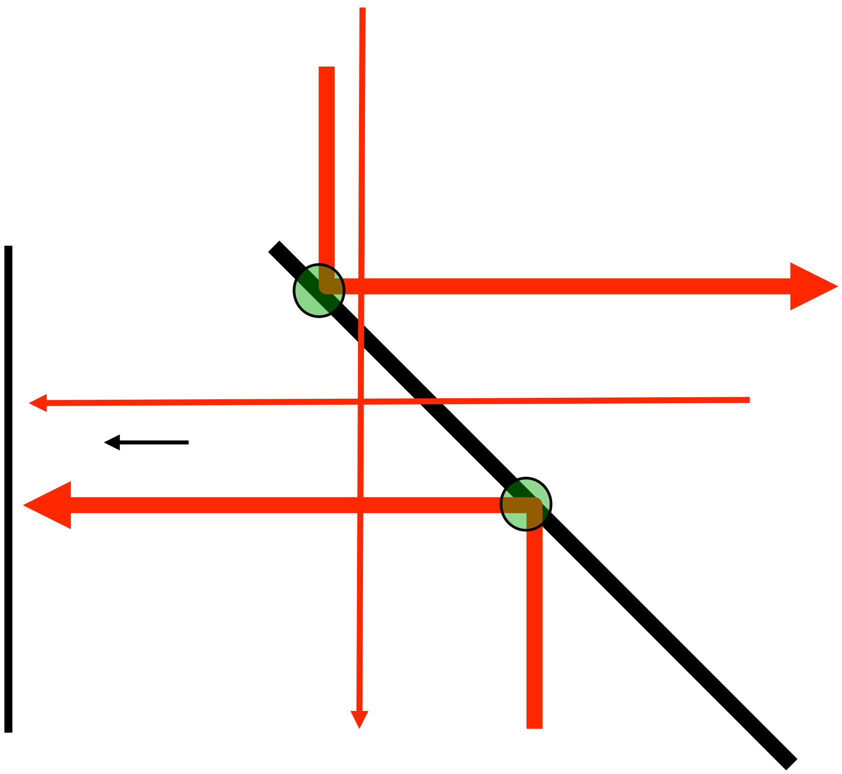
Beamsplitter: reflection events at two times separated by $L=2L_0$

Measurement of transverse position of beamsplitter

- Positions of reflection events have transverse uncertainties

$$\sigma'\sigma = \lambda L$$

- Independent samplings accumulate signal phase uncertainty
- apparent arm length difference is a random variable, with variance:

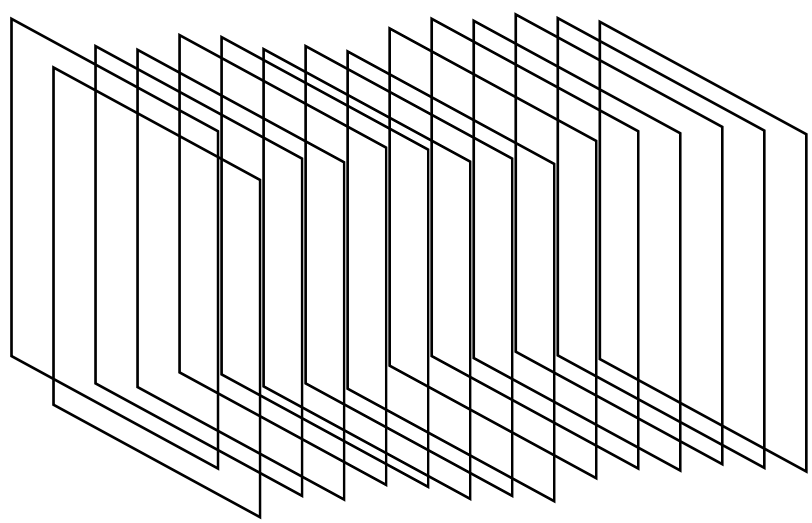


$$\Delta L_0^2 = \sigma^2 + \sigma'^2 = 2\sigma^2 = 4 l_P L_0$$

this is a new effect predicted with no parameters

“continuous measurement”~ transverse Planck random walk

- A highly interactive system mimics a random walk transverse to null direction of propagation (normal measurement): a Planck length per Planck time
- Walk in the position of bodies (e.g., beamsplitter) and not propagating radiation itself



Power Spectral Density of Fluctuations

Uncertainty in angle ~ dimensionless metric perturbation

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

~ metric shear 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:*

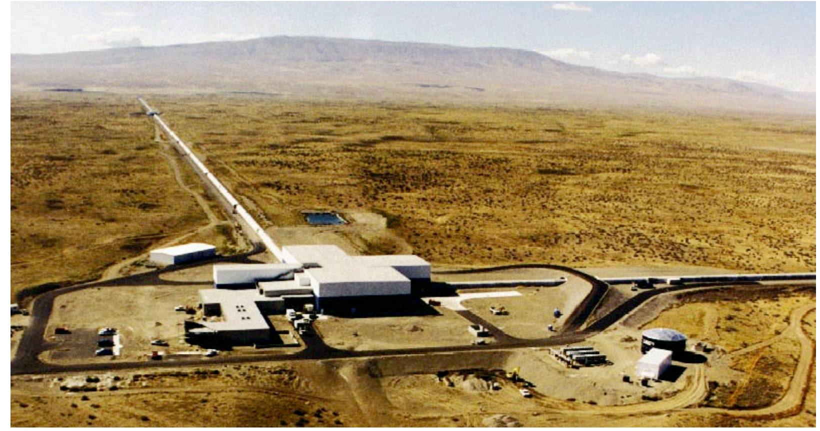
$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22} \mathrm{Hz}^{-1/2}$$

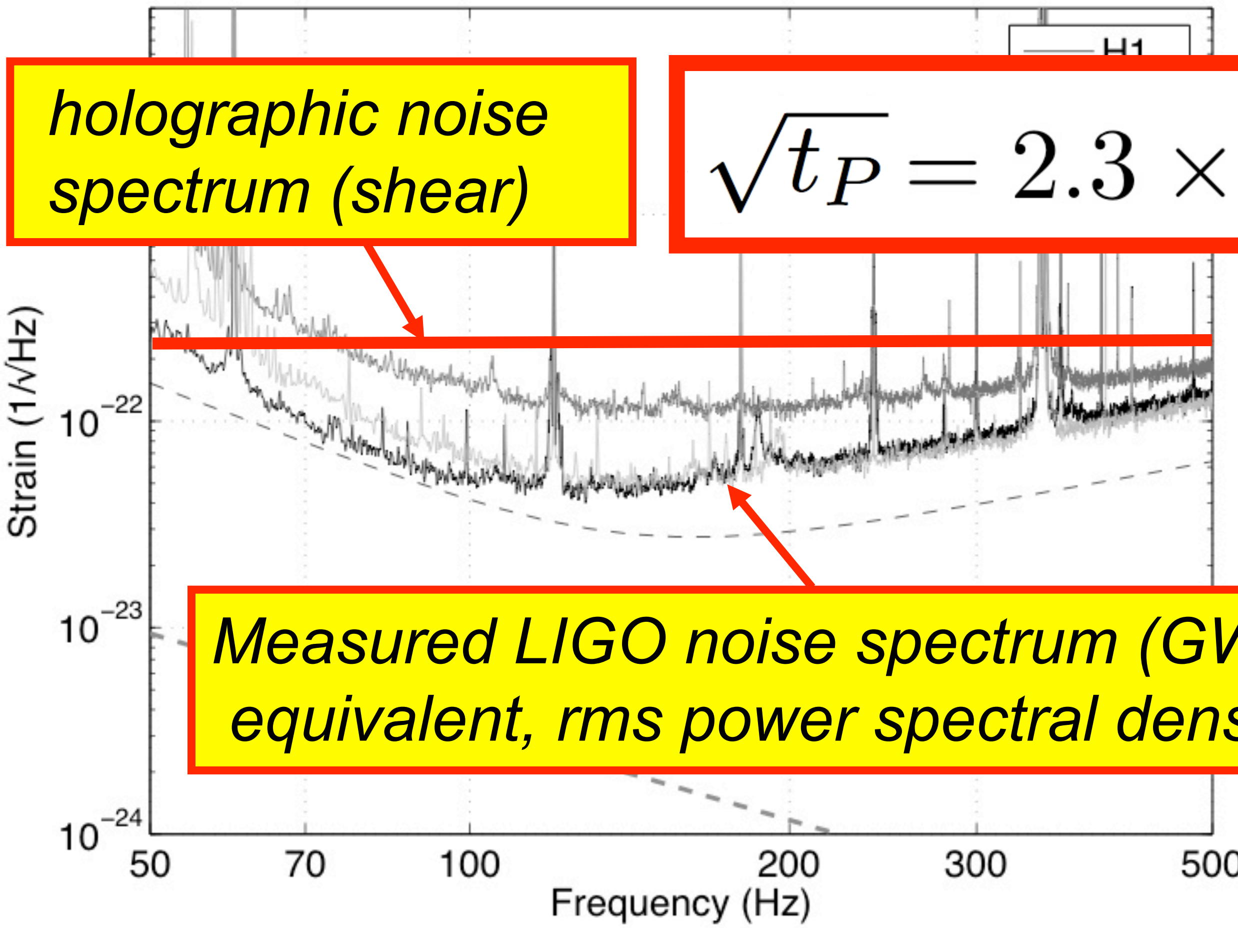
- A property of holographic quantum geometry
- Prediction of spectrum with no parameters
- Prediction of spatial shear character: only detectable in transverse position observables
- Definitively falsifiable
- Contrast with more general range of possible phenomenology (e.g. Amelino-Camelia, et al.)

Holographic fluctuations do not carry energy or information

- ~ classical gauge mode (flat space, no classical spacetime degrees of freedom excited)
- ~sampling noise, not 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 noise (astro-ph/0608606)

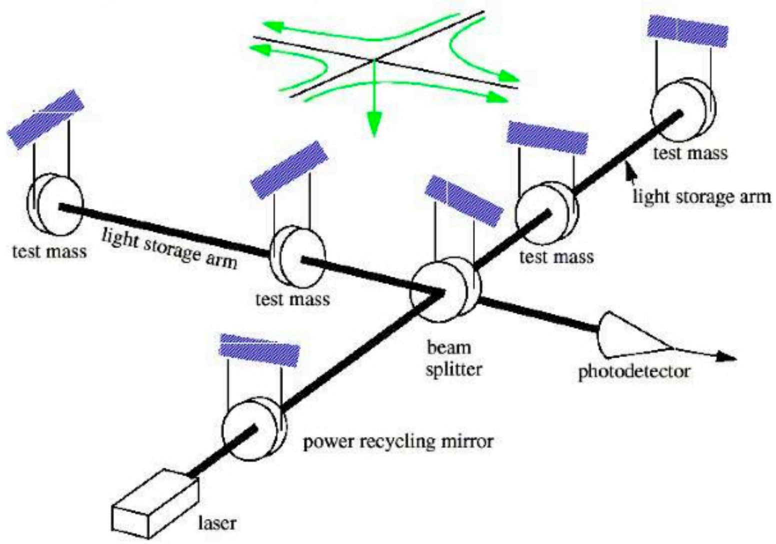




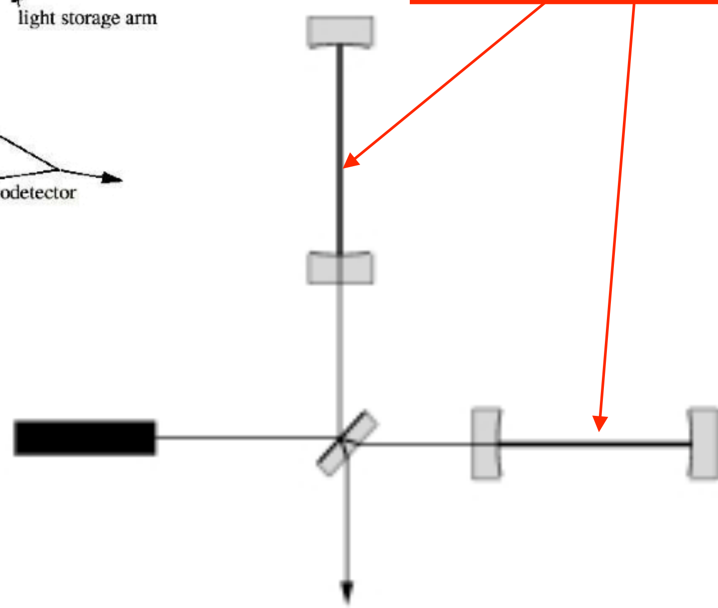
Why doesn't LIGO detect holographic noise?

- 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.

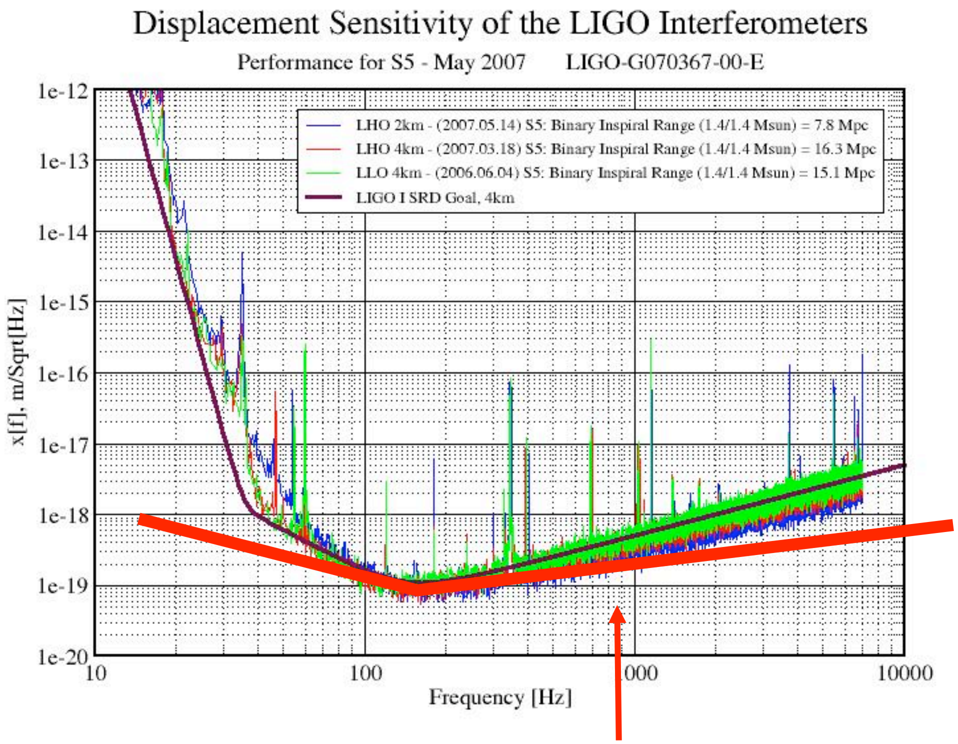


Transverse position measurement is not made in FP cavities



LIGO S5 run: noise in displacement units

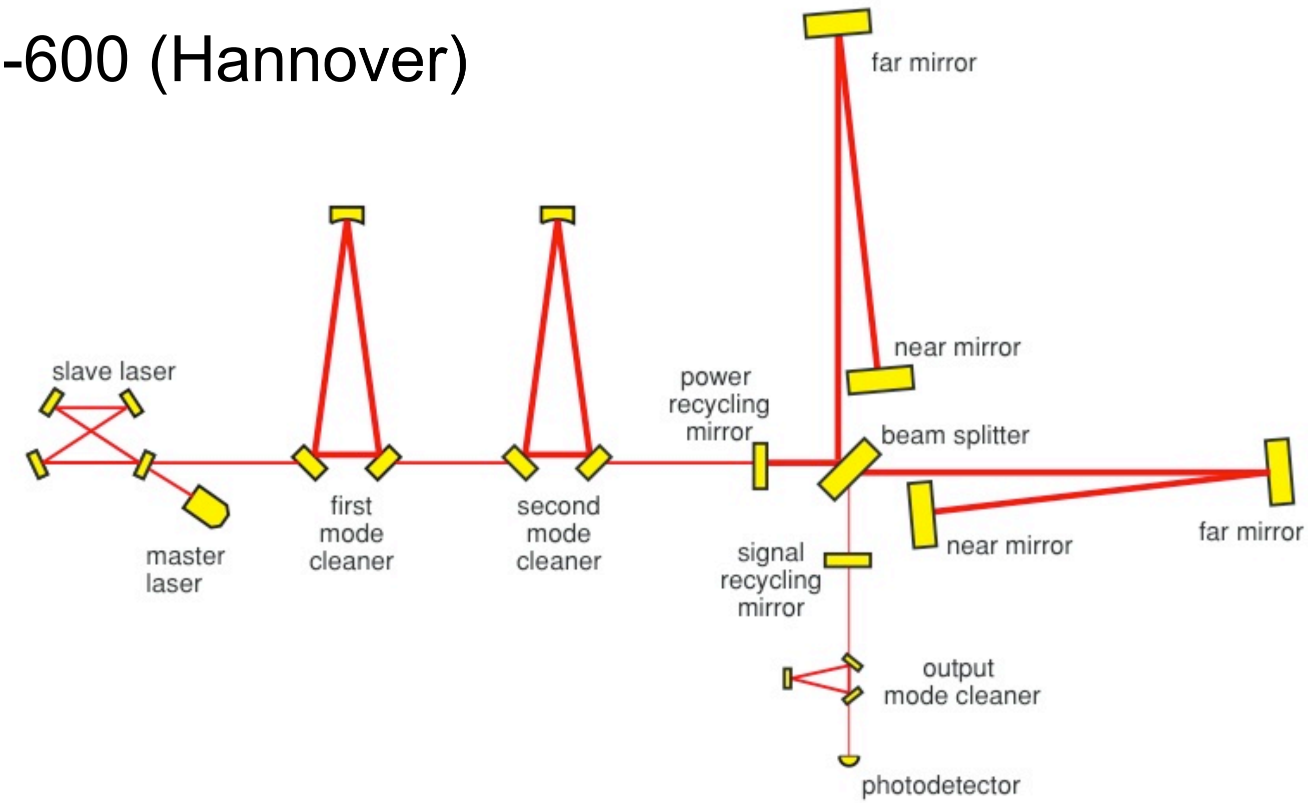
- Allow for lack of holographic noise from FP arm cavities
- In displacement units, estimated holographic noise is below sensitivity of last science run
- Will be detectable with enhanced/advanced LIGO



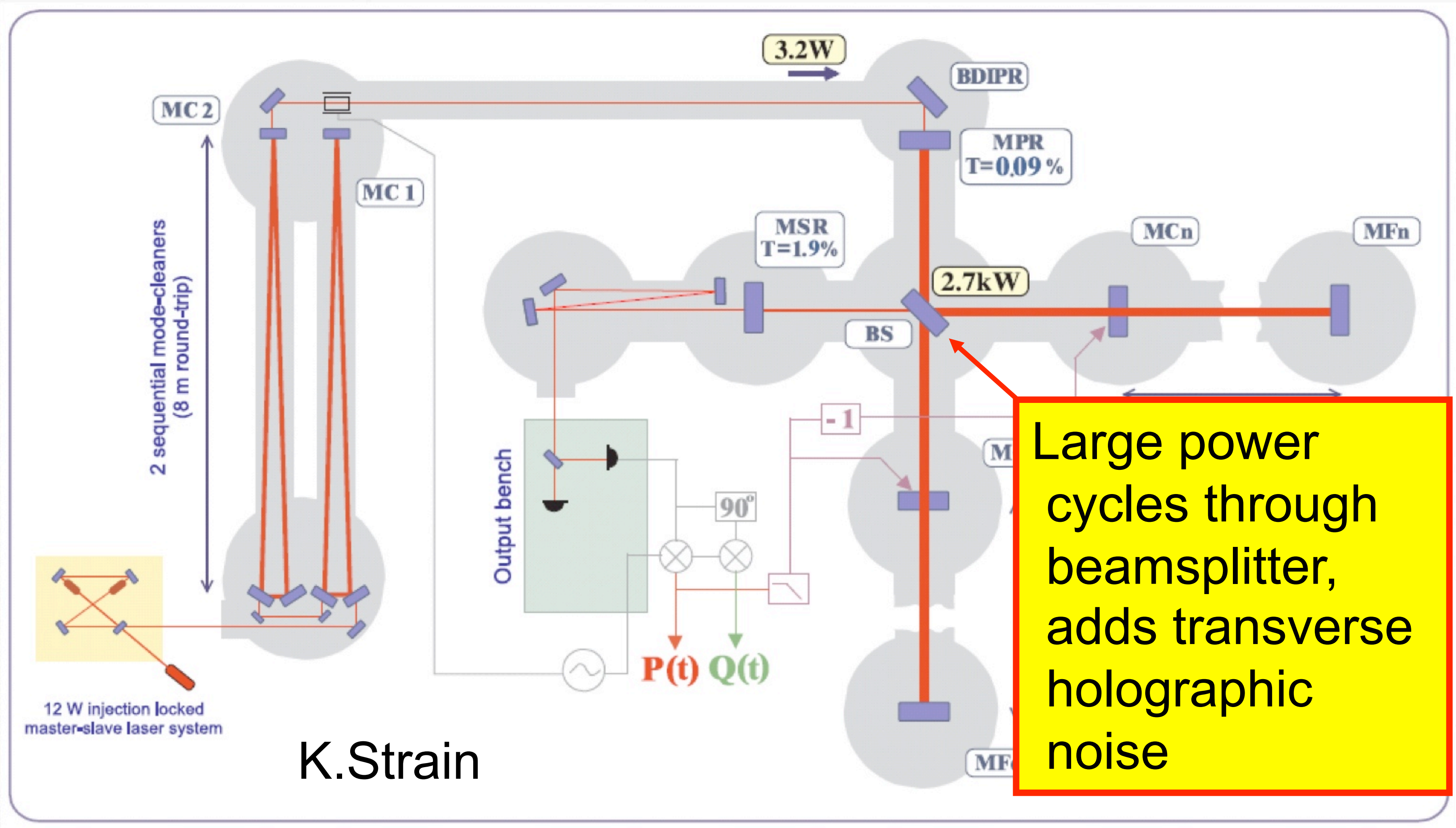
Rough but zero-parameter estimate of holographic noise in LIGO (displacement units)

CJH: **arXiv:0806.0665**

GEO-600 (Hannover)



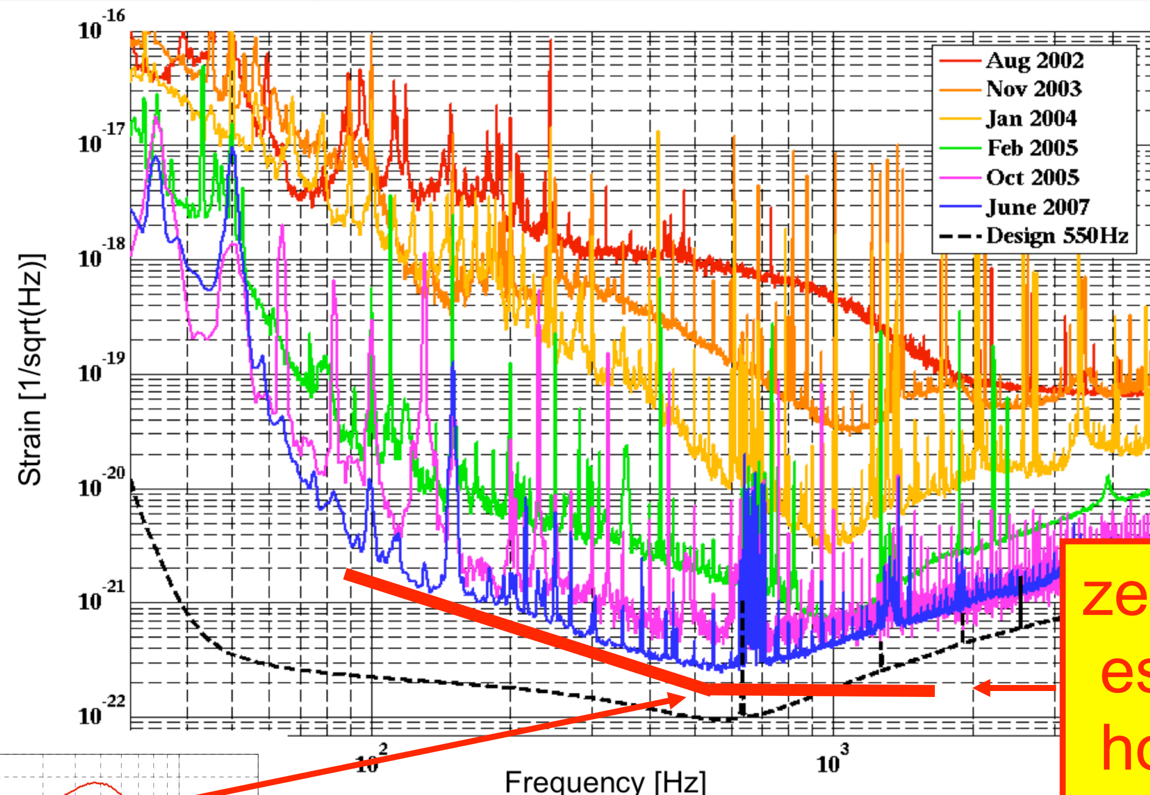
The GEO600 Interferometer

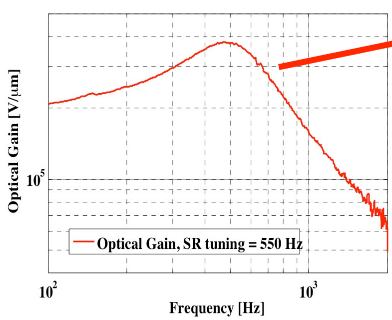


Noise in GEO600

GEO Sensitivities

K.Strain

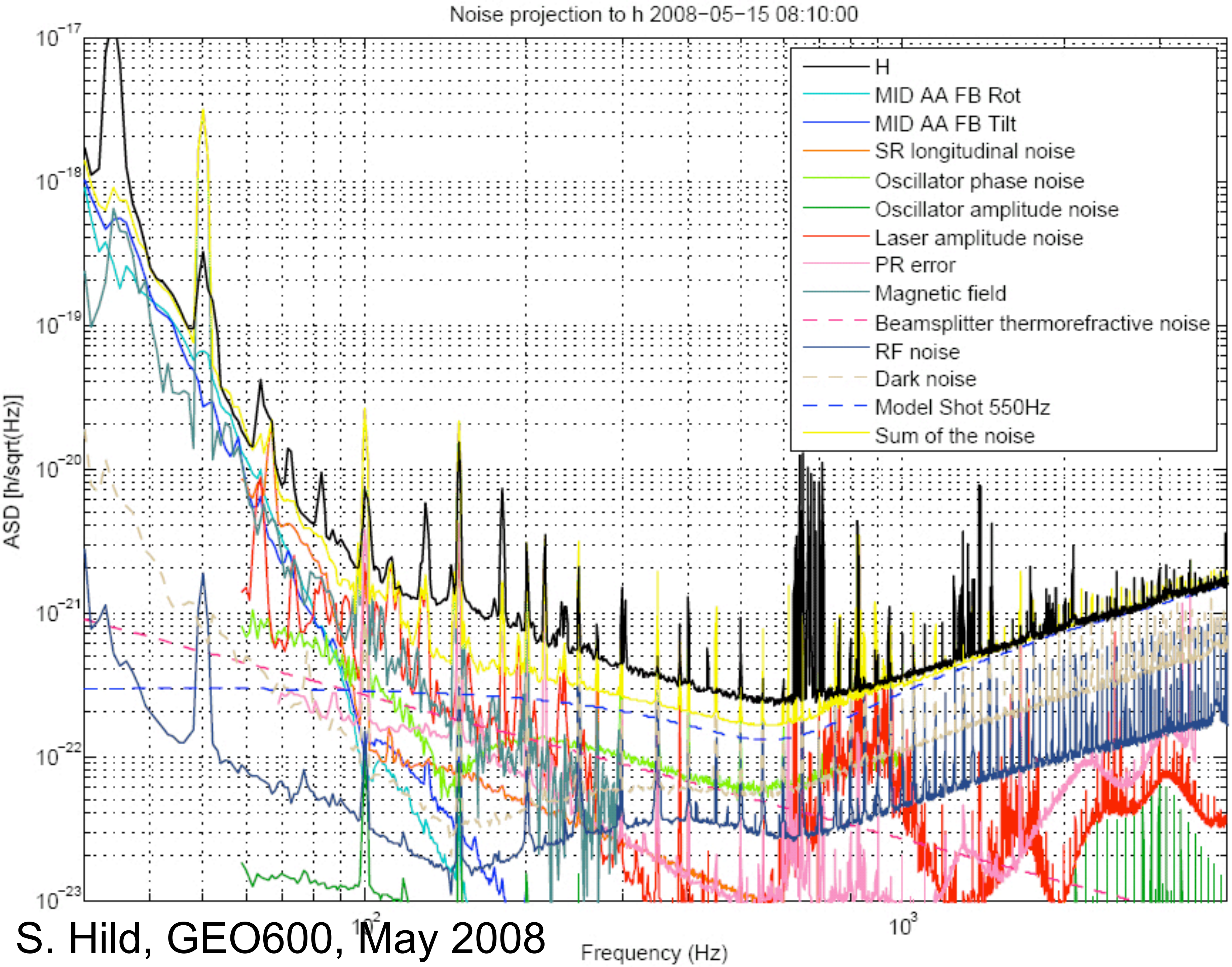




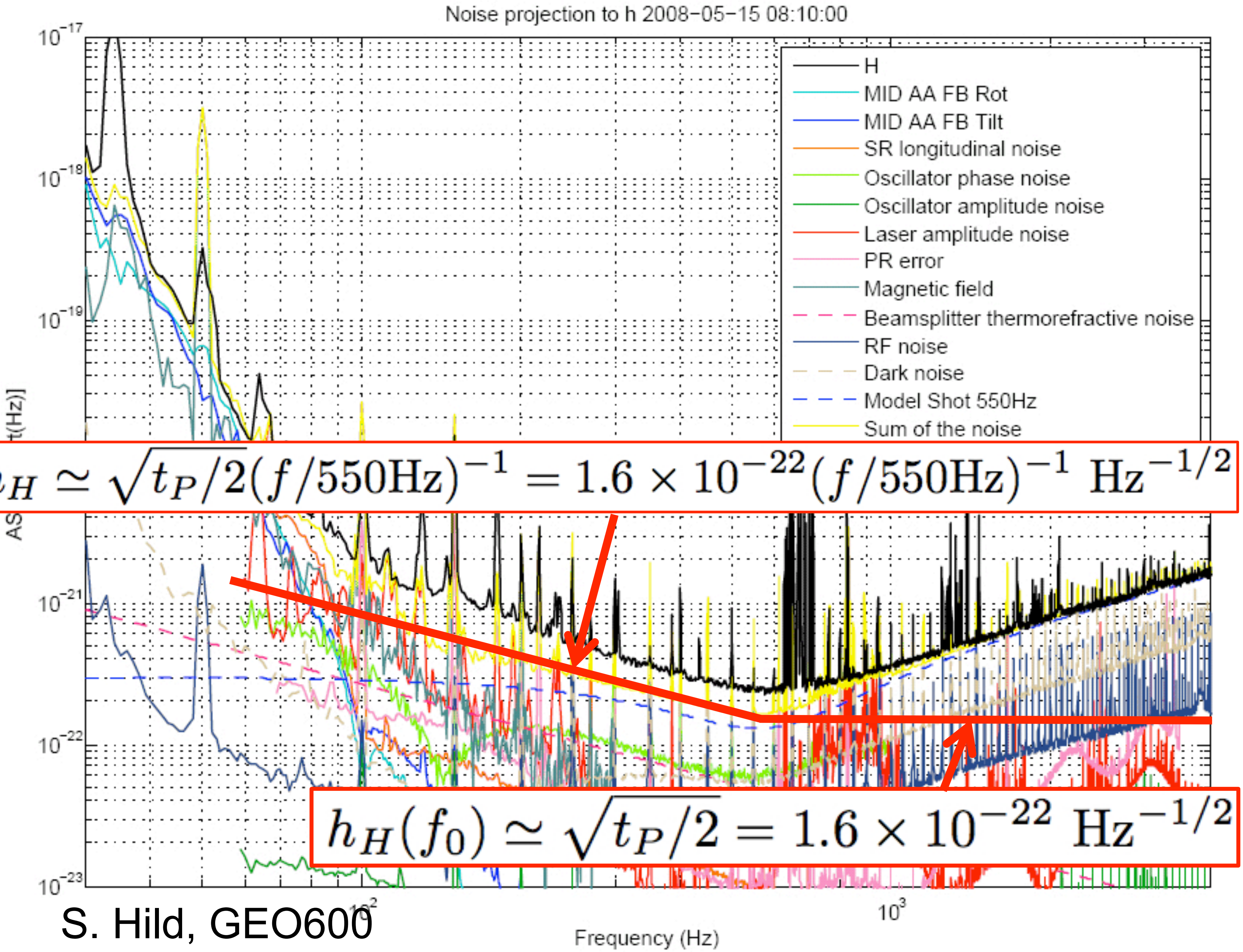
zero-parameter estimate of holographic noise in GEO600 (equivalent strain)

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

CJH: arXiv:0806.0665



S. Hild, GEO600, May 2008

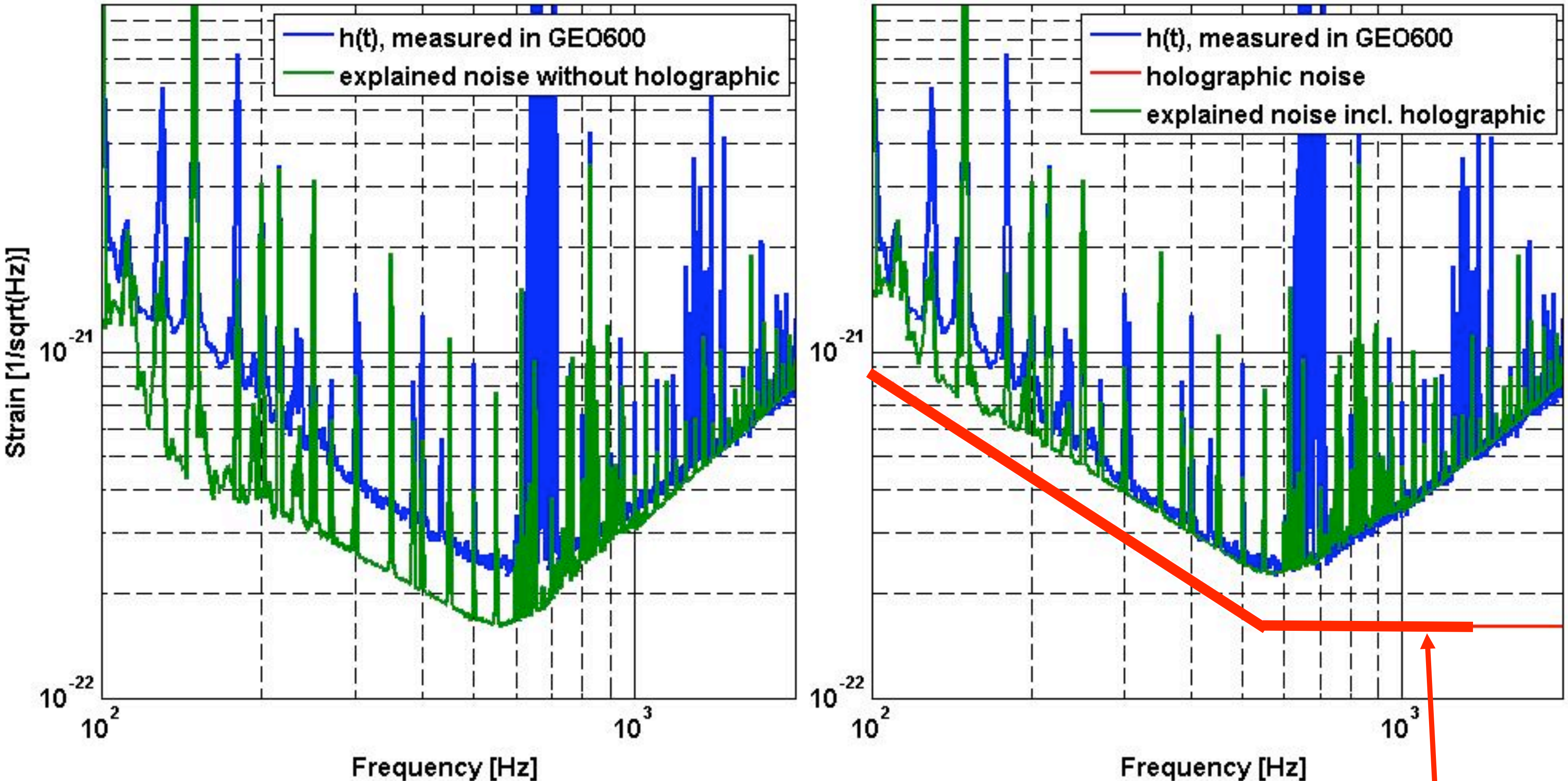


$$h_H \simeq \sqrt{t_P/2}(f/550\text{Hz})^{-1} = 1.6 \times 10^{-22}(f/550\text{Hz})^{-1}\ \text{Hz}^{-1/2}$$

$$h_H(f_0) \simeq \sqrt{t_P/2} = 1.6 \times 10^{-22}\ \text{Hz}^{-1/2}$$

S. Hild, GEO600

"Mystery Noise" in GEO600



zero-parameter prediction for holographic noise in GEO600 (~ equivalent strain)

Data: S. Hild (GEO600)

Prediction: arXiv:0806.0665

Total noise: not fitted

Current experiments

- Most sensitive device, GEO600, sees noise compatible with holographic spacetime indeterminacy
- other explanations, e.g. thermorefractive noise 3.6 times larger than expected in the model, need to be checked
- requires testing and confirmation!
- H. Lück: "...it is way too early to claim we might have seen something."
- LIGO: current data close but may not be sensitive enough, awaits next upgrade
- Models of holographic noise in signals of both systems can be improved

Interferometers can detect quantum indeterminacy of geometry

- Beamsplitter inserts holographic uncertainty into signal
- **system with LIGO, GEO600 technology can detect holographic noise if it exists**
- Signatures: spectrum, spatial shear

CJH: **arXiv:0806.0665**

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
- Optimal designs different from GW studies
- Different scales: atom interferometers

Program for holographic noise experiments

- Measure quantum indeterminacy of spacetime
- Measure non-pointlike, wave character of events
- Measure nonlocal quantum weirdness of spacetime metric
- Connect quantum geometry in the lab with information limits from complete fundamental theory (2+1D null projection, black hole entropy, string theory etc.)
- Clues to nature of vacuum-fluctuation gravity, quantum physics of Dark Energy