The Fermilab Holometer:

A program to measure Planckian indeterminacy associated with unification

Craig Hogan

Fermilab and U. Chicago

Agenda for the mini-review

Craig: Science motivation, background, overall scope (30 +10 min)
Aaron and Rai: Experimental design and challenges (30 + 10)
William: Schedule, Budget, Participants (20 +10)
Erik: Site options (10+10)
Jason: Future reconfiguration options (10+10)
Chris: Initial prototyping, control strategy (10+10)

Documents:

Expression of interest for PAC (draft of 7 June 09)

“Holographic Noise in Interferometers” (http://arxiv.org/abs/0905.4803)

“Concept for an interferometric test of Hogan's quantum geometry hypothesis”, 2/10/2009

Unification Experiments

- Physics=classical spacetime+quantum fields (mass-energy)
- Both are approximations
- We have candidate theories of everything: spacetime, mass-energy
- We have no experimental tests
- What are the macroscopic, classical limits?
- What phenomena can guide theory?

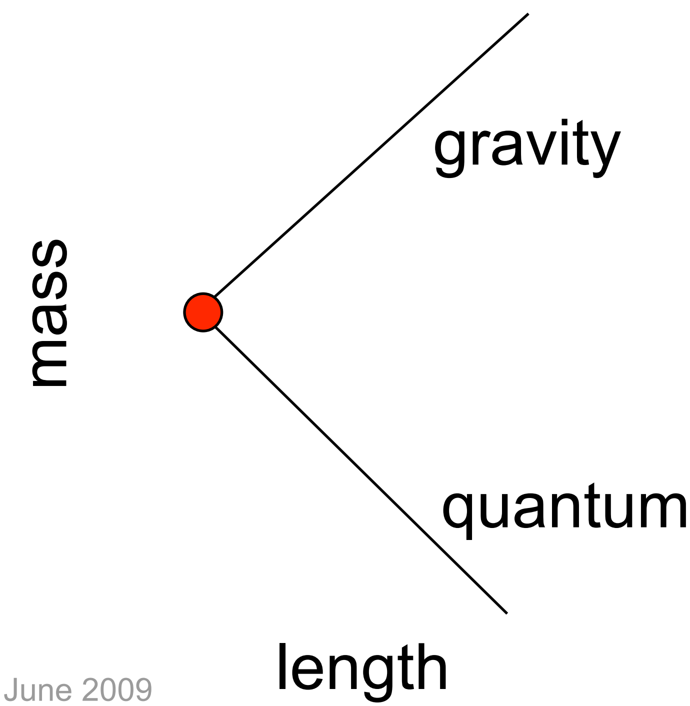
Planck scale: spacetime merges with mass-energy

- Quantum gravity suggests a minimum (Planck) time,

$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \quad \text{seconds}$$

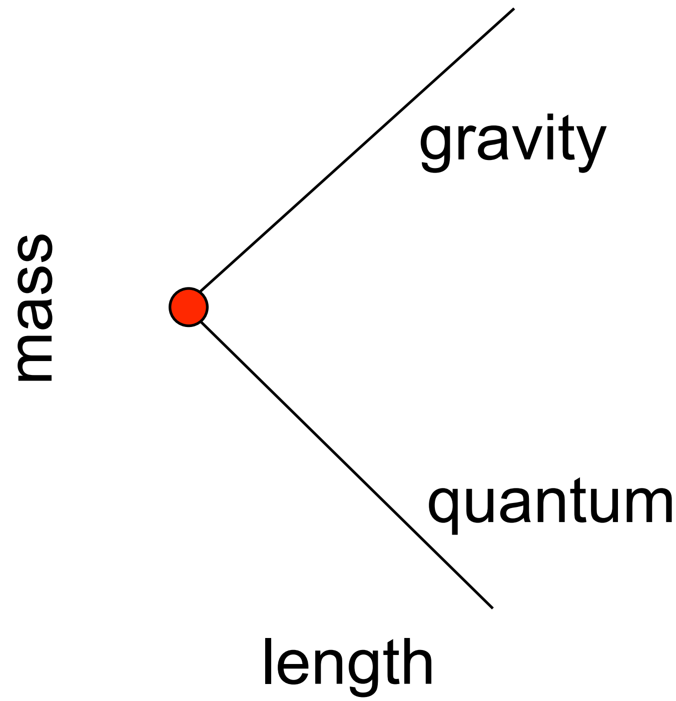
$$l_P = \sqrt{\hbar G_N/c^3} = 1.616 \times 10^{-33}\text{cm}$$

- ~ particle energy 10^{16} TeV



Two approaches to the Planck scale

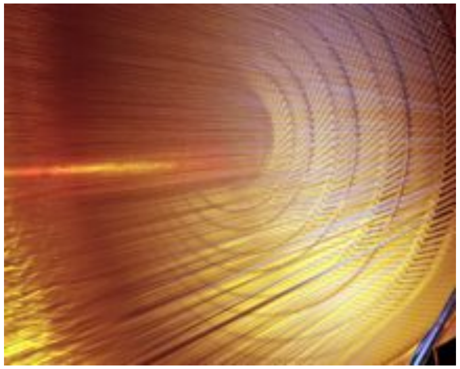
Position wavefunctions



Particle states

Best microscopes vs best microphones

CERN/Fermilab: $TeV^{-1} \sim 10^{-18}$ m: particle interactions



LIGO/GEO600: $\sim 10^{-18}$ m, over $\sim 10^{3}$ m:
Positions of massive bodies

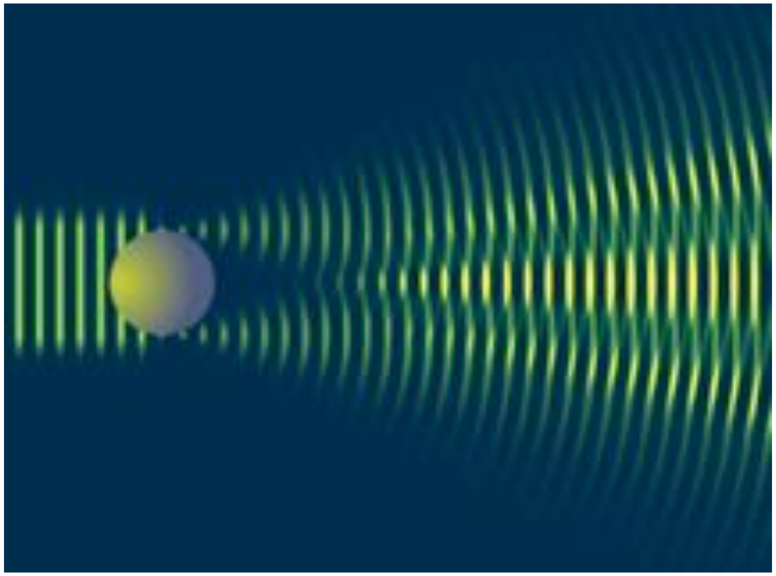
A new phenomenon?: holographic noise

- The Planck limit may affect interferometers
- uncertainty much larger than Planck scale in a particular interpretation of holographic theories
- precise, zero-parameter prediction: “Holographic Noise”

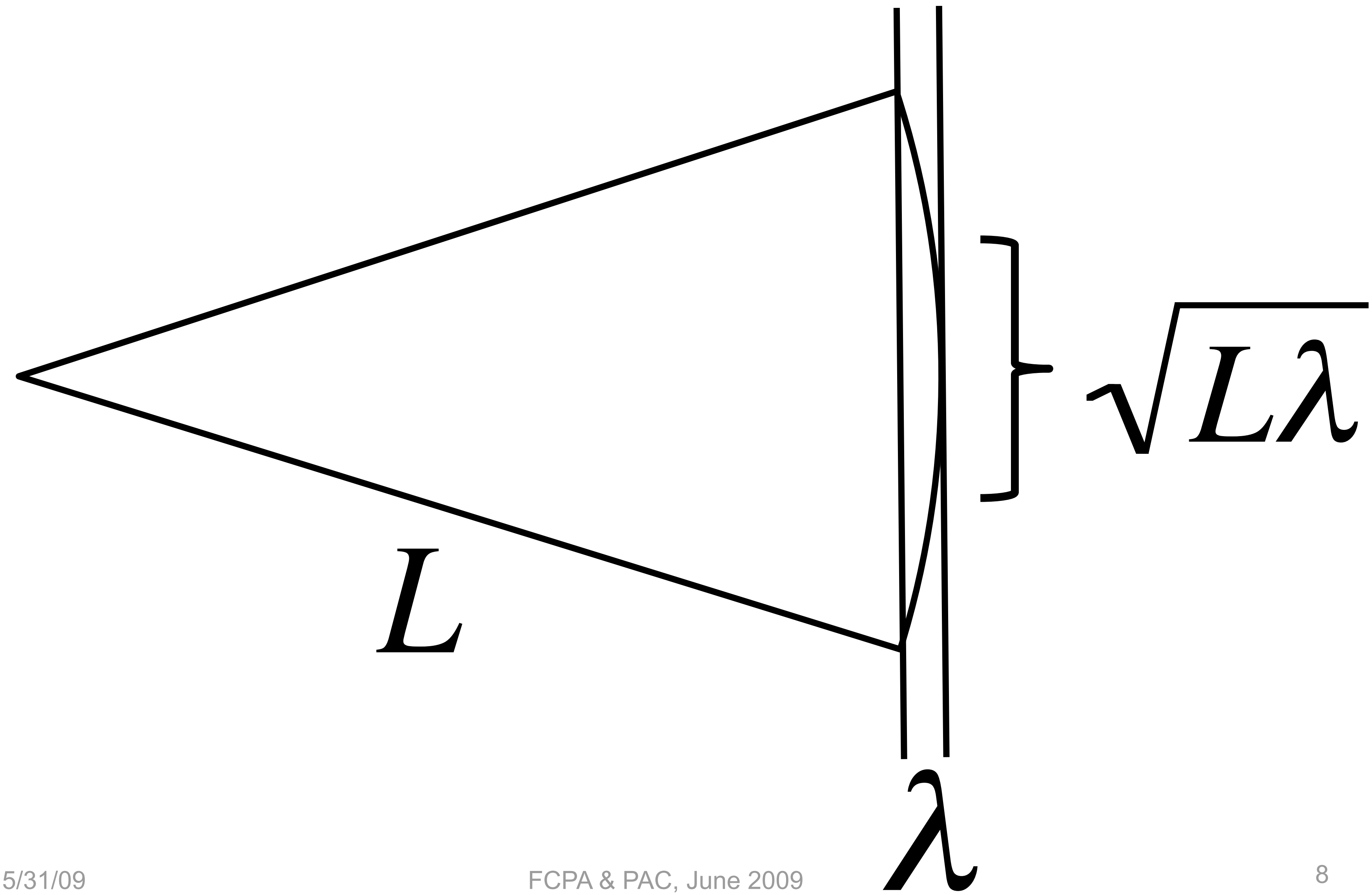
“Planck diffraction limit” at *L*

$$\Delta x \sim \sqrt{\lambda L}$$

is >> Planck length

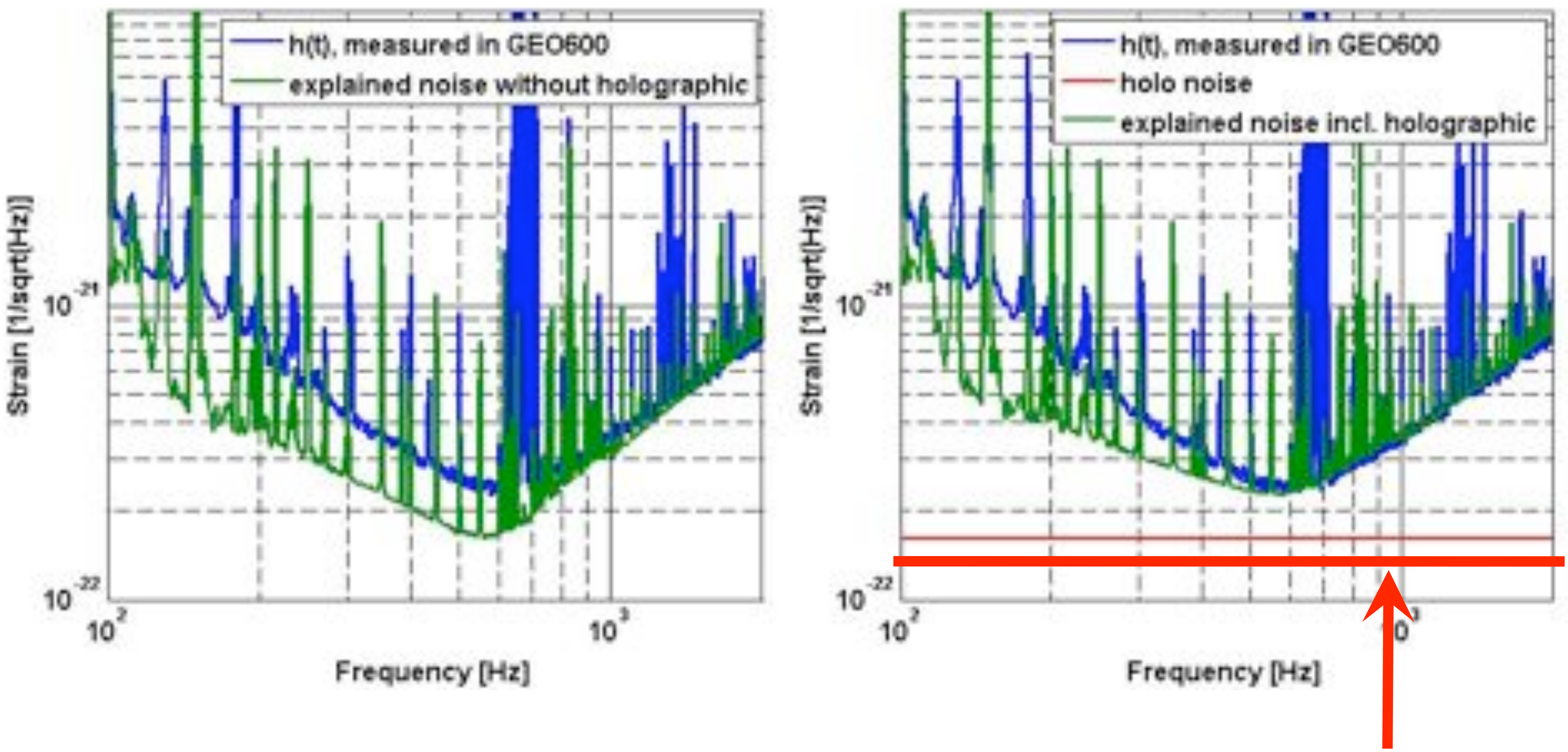


Spatial frequency limit causes indeterminacy: transverse position wavefunction at distance *L*



GEO-600 (Hannover): best displacement sensitivity

“Mystery Noise” in GEO600



$$\sqrt{t_{Planck}/\pi}$$

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

Data: S. Hild (GEO600)

Prediction: CJH, arXiv:0806.0665
(Phys Rev D.78.087501)

Total noise: not fitted

Measurement of holographic noise

- Holographic wave geometry predicts a new detectable effect: "holographic noise"
- Not the same as zero-point field mode fluctuations
- Spectrum and spatial character predicted with no parameters
- It may already be detected
- An experimental program is motivated

CJH: arXiv:0806.0665 Phys Rev D.78.087501 (2008)

CJH: arXiv:0712.3419 Phys Rev D.77.104031 (2008)

CJH and M. Jackson:arXiv:0812.1285 PhysRevD.79.124009

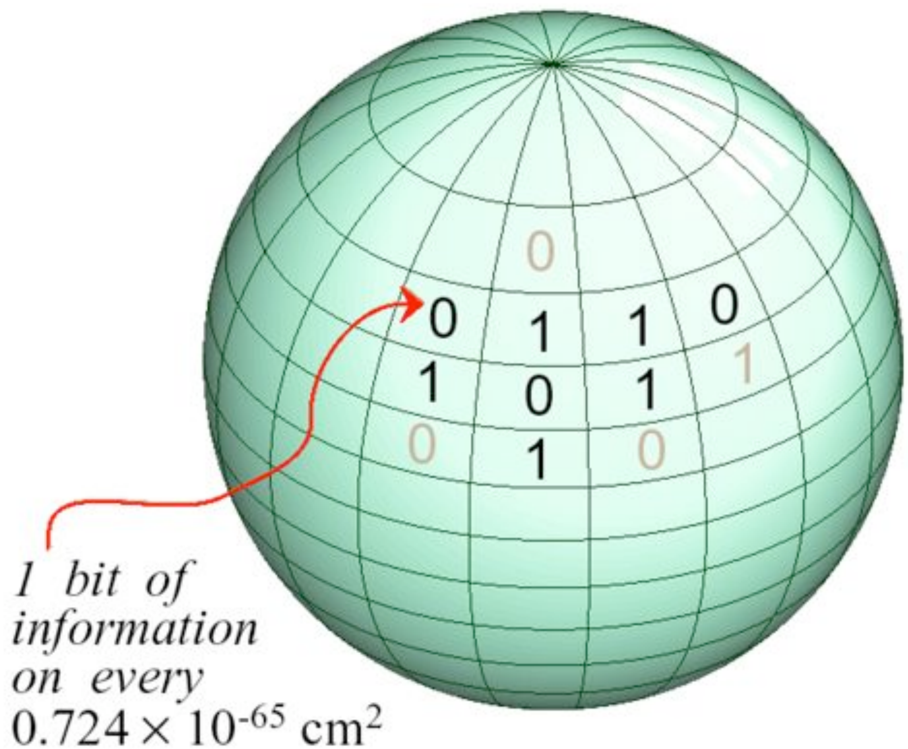
CJH: arXiv:0905.4803

Holographic Theories of Everything

“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 null surface at Planck resolution



Holographic geometry: a phenomenological layer

Fundamental theory (Matrix, string, loop,…)

↕

Holographic geometry (paraxial waves, diffraction, transverse spacetime wavefunction, holographic uncertainty…)

↕

Observables in classical apparatus (effective beamsplitter motion, holographic noise in interferometer signals)

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
- Matrix theory
- All suggest theory on 2+1 dimensional null surfaces with Planck frequency bound

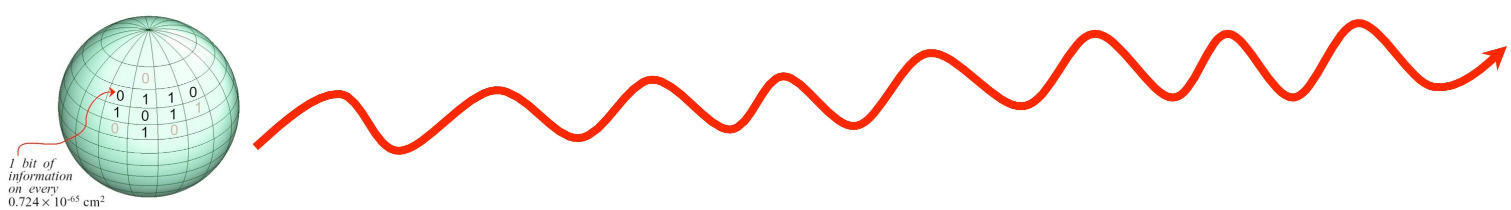
Beckenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Padmanabhan, Banks, Fischler, Shenker, Unruh

Holography 1: Black Hole Thermodynamics

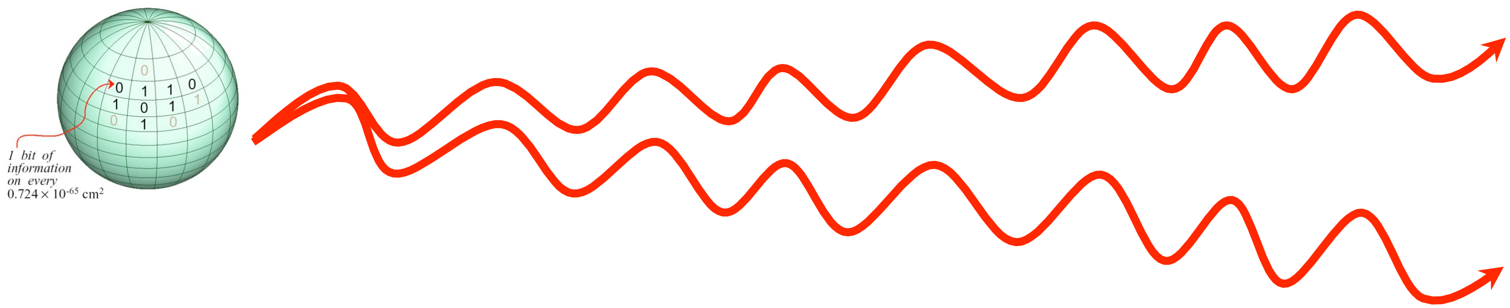
- Beckenstein, Bardeen et al. (~1972): laws of black hole thermodynamics
- Area of (null) event horizon, like entropy, always increases
- Entropy is identified with 1/4 of event horizon area in Planck units (not volume)
- Is there is a deep reason connected with microscopic degrees of freedom of spacetime encoded on the surface?

Holography 2: Black Hole Evaporation

- Hawking (1975): black holes radiate ~thermal radiation, lose energy and disappear
- evaporated quanta carry off degrees of freedom (~1 per particle) as area decreases
- States on 2D event horizon completely account for information of evaporated states, assembly histories
- Information of evaporated particles=entropy of hole= *A/4*

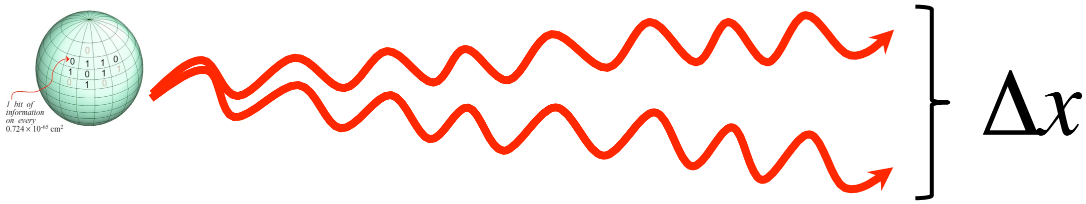


black hole evaporation can obey quantum mechanics if distant, nearly flat space has transverse indeterminacy



If the quantum states of the evaporated particles allowed relative transverse position observables with arbitrary angular precision, at large distance they would contain more information than the hole

Holographic uncertainty and black hole evaporation



- ~ One particle evaporates per Planck area
- position recorded on film at distance *L*
- wavelength ~ hole size *R*
- standard position uncertainty $\Delta x > R$

- Particle images on distant film: must have fewer “pixels” than hole

$$(L/\Delta x)^2 < (R/\lambda)^2$$

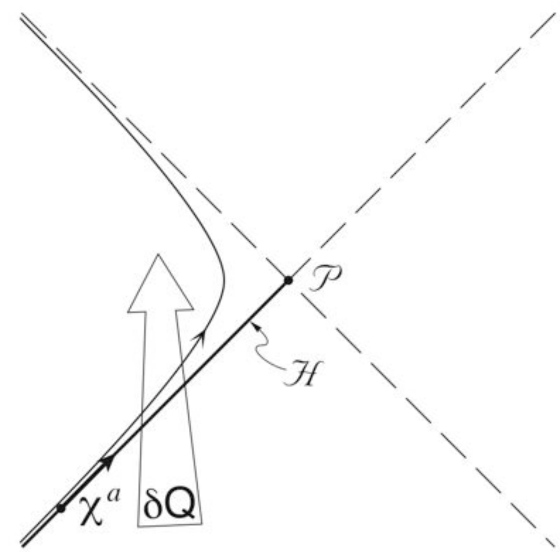
- Requires transverse uncertainty at distance *L* independent of *R*

$$\Delta x > \sqrt{\lambda L}$$

- Uncertainty of flat spacetime independent of black hole mass
- Similarly for number of position states of an interferometer

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

Holography 5: Exact dual theories in N-1 dimensions

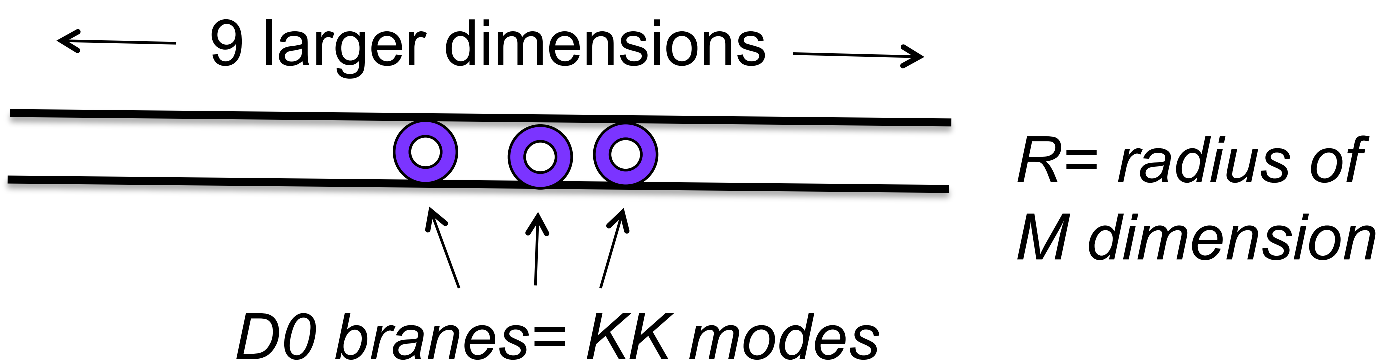
- Maldacena, Witten et al. (1997…): AdS/CFT correspondence
- N dimensional conformal field "boundary" theory exactly maps onto (is dual to) N+1 dimensional "bulk" theory with gravity and supersymmetric field theory
- Is nearly flat 3+1 spacetime described as a dual in 2+1?

Holography 6: 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
- Strong indication of a minimum length ~ Planck length
- What do the degrees of freedom look like in a realistic system?
- Matrix theory: wavefunctions of transverse position Matrix Hamiltonian (CJH& M. Jackson)

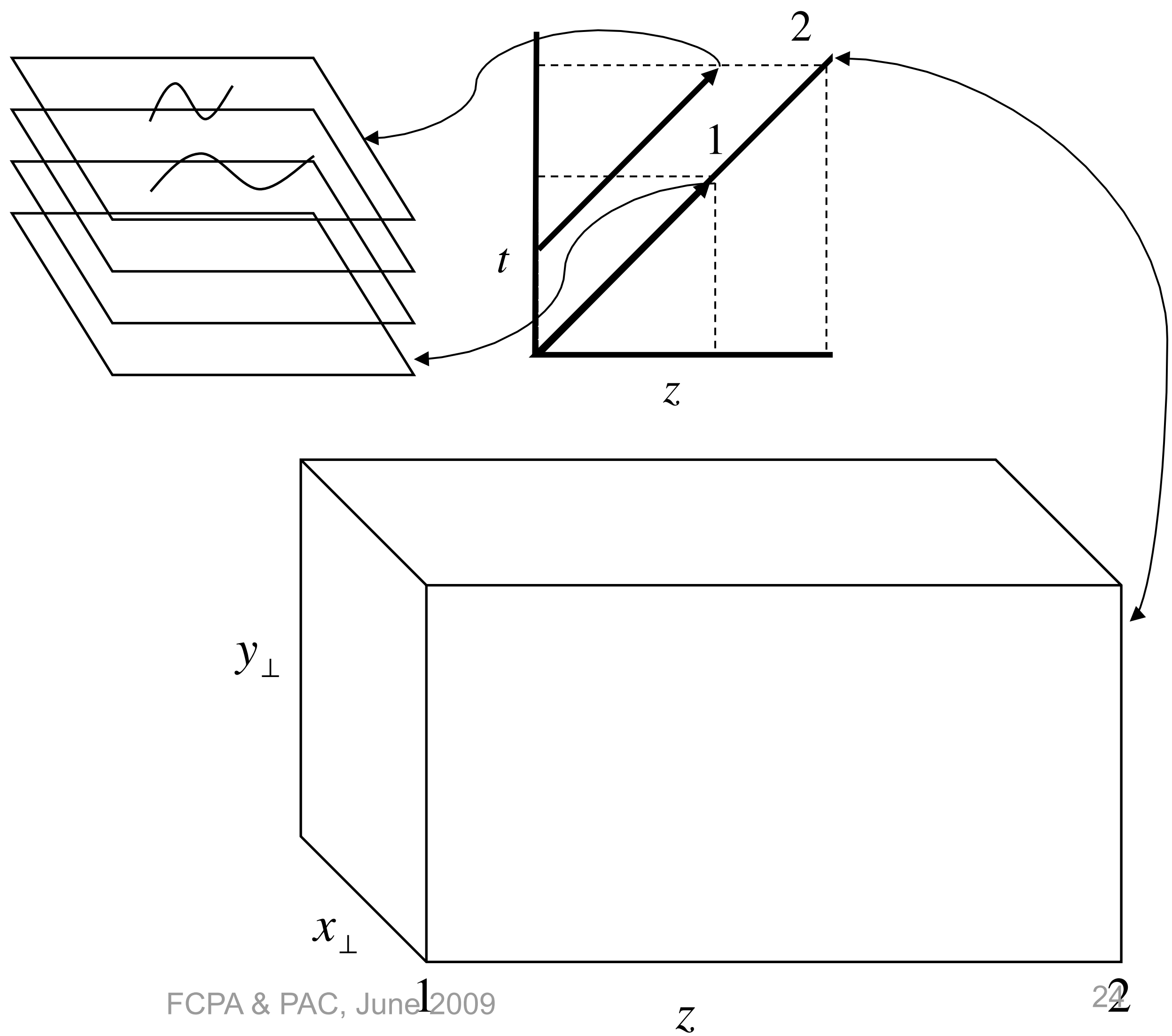
Example: Matrix theory

- Banks, Fischler, Shenker, & Susskind 1997: a candidate theory of everything
- Fundamental objects are 9 N x N matrices, describing N “D0 branes” (particles)
- Dual relationship with string theory
- Gives rise to 10 space dimensions, 1 compact, plus time



- Only 2 space dimensions are macroscopic
- The third space dimension is virtual, swept out by 2D null sheet

3+1D spacetime emerges from 2+1D: light sheet with z=t



Holographic spacetime: wave theory from M theory

- N D0 branes, N x N matrices X_i, , i= 1 to 9, compact M dimension with radius R ~ Planck length
- Hamiltonian from Banks, Fischler, Shenker, & Susskind:

$$H = R \operatorname{tr} \left\{ \frac{\Pi_i \Pi_i}{2} + \frac{1}{4}[X_i, X_j]^2 + \theta^T \gamma_i [\theta, X_i] \right\}$$

- Notions of position, distance emerge on scales >>R
- local in 2+1 D, "incompressible" on Planck scale: holographic
- Center of mass position of macroscopic mass-energy, x= tr X
- Macroscopic longitudinal position encoded by first (kinetic) term,conjugate momenta to position matrices

CJH and M. Jackson:arXiv:0812.1285 PhysRevD.79.124009

Macroscopic wave equation from M theory

- M Hamiltonian stripped to macroscopic essentials

$$\hat{H} = \frac{R}{2\hbar} tr\hat{\Pi}^2$$

- substitute

$$R \rightarrow k^{-1} = \lambda/2\pi$$

$$tr\hat{\Pi}^2 \rightarrow -\hbar^2\partial^2/\partial x^2,$$

$$\hat{H} \rightarrow i\hbar\partial/\partial z^+,$$

Macroscopic wave equation from M theory

$$\hat{H} = \frac{R}{2\hbar} tr \hat{\Pi}^2$$

becomes

$$\frac{\partial^2 u}{\partial x^2} + \frac{4\pi i}{\lambda} \frac{\partial u}{\partial z^+} = 0$$

- Schrodinger equation, with z^+ as time dimension and *u(x)* a wavefunction of one transverse position
- Quantum mechanics without Planck's constant

Solutions of wave equation mix dimensions

$$\frac{\partial^2 u}{\partial x^2} + \frac{4\pi i}{\lambda}\frac{\partial u}{\partial z^+} = 0$$

Solutions display diffusion, diffraction:

$$u(x, z^+) = \sum_{k^\perp} A_{k^\perp} \exp -i[k^+ z^+ \pm k^\perp x]$$

$$k^\perp = \sqrt{4\pi k^+/\lambda}$$

New uncertainty principle: transverse widths of wavepackets

$$\frac{\partial^2 u}{\partial x^2} + \frac{4\pi i}{\lambda}\frac{\partial u}{\partial z^+} = 0$$

$$\langle \Delta x^2 \rangle \langle \Delta k^{\perp 2} \rangle \geq 16\pi^2$$

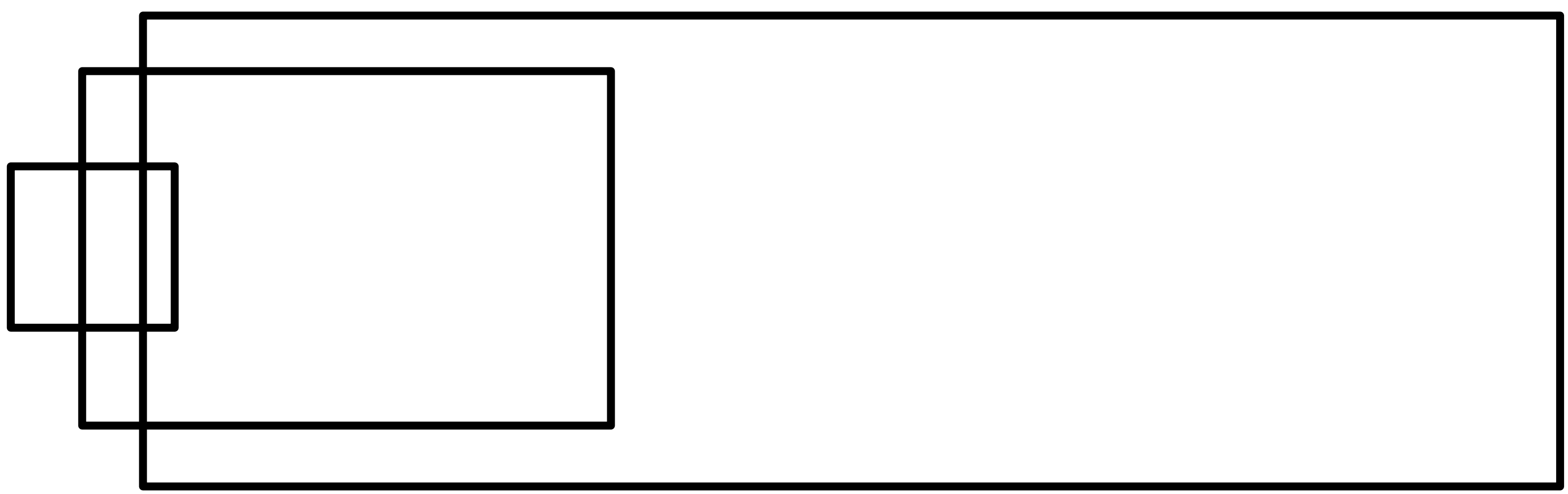
$$\Delta L^+ \equiv (4\pi/\lambda)(2\pi/\langle \Delta k^{\perp 2} \rangle)$$

$$\langle \Delta x^2 \rangle > \lambda \Delta L^+/2$$

Nonlocal modes connect longitudinal and transverse positions

- Wave solutions: “Holographic geometry”
- Transverse gaussian beam solutions from wave optics
- New macroscopic behavior, not the same as field theory limit

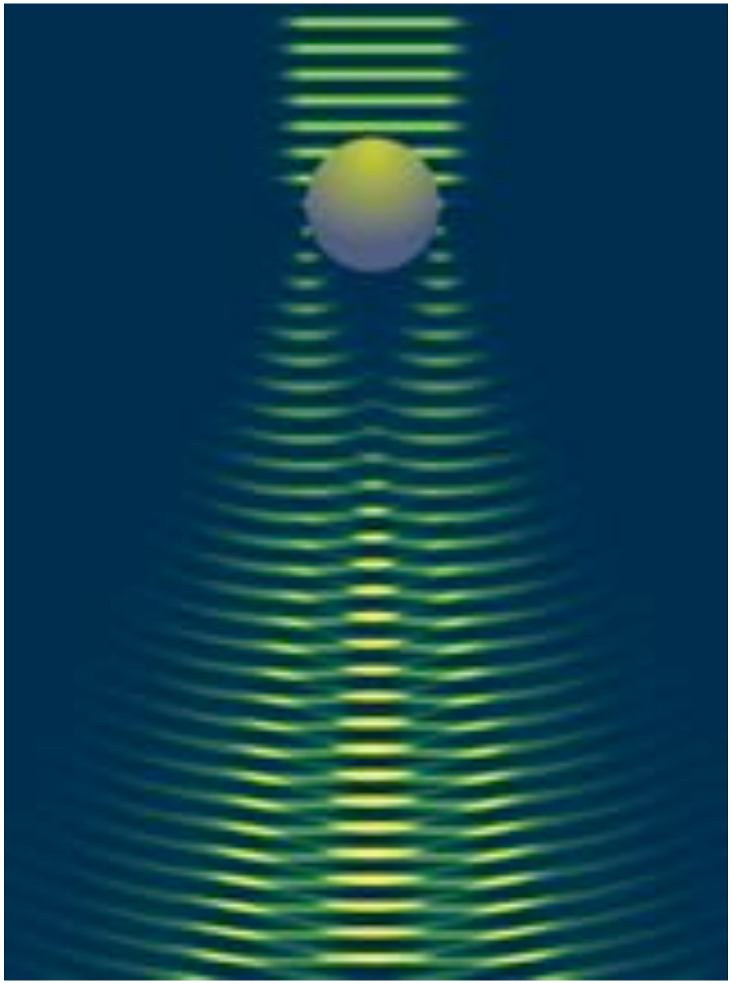
x



z,t

Wave Theory of Spacetime

- Adapt wave optics to theory of "spacetime wavefunctions"
- transverse indeterminacy from diffraction of Planck waves
- Allows calculation of holographic noise with no parameters



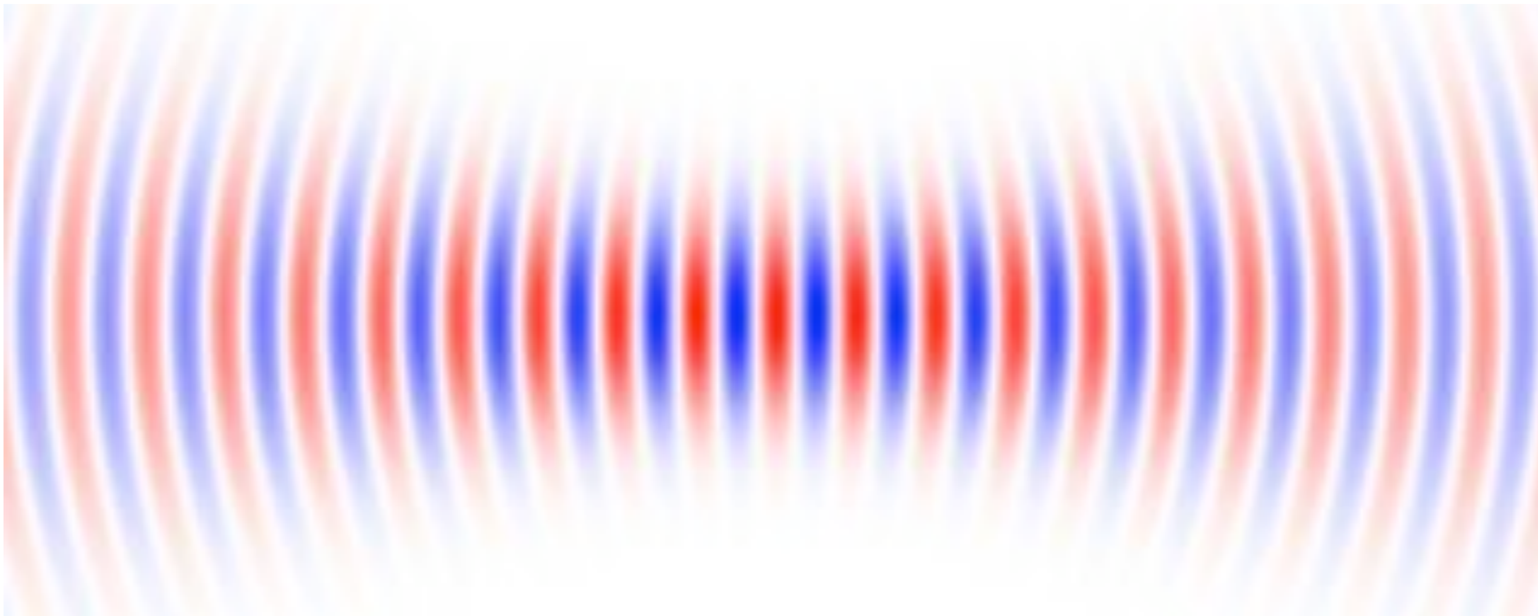
Paraxial wave equation

- phasors in wavefronts: wavefunction relative to carrier
- wave equation in each transverse dimension *x*

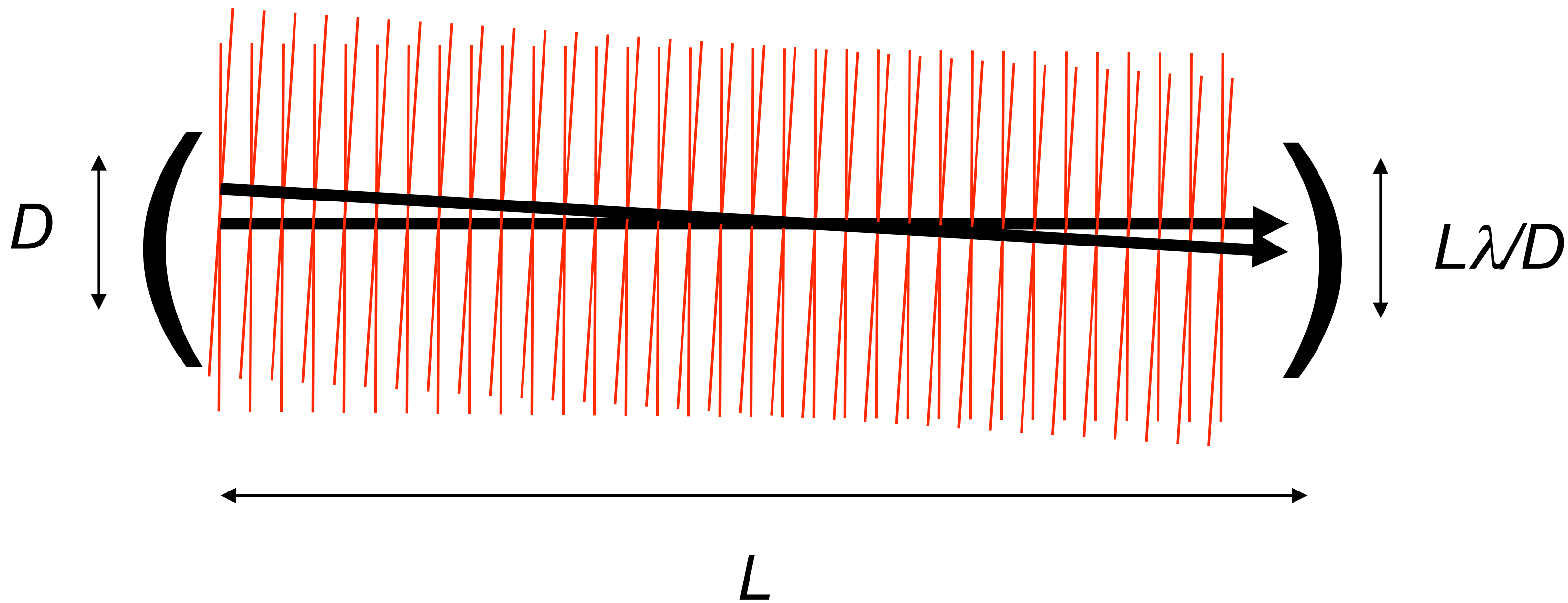
$$\frac{\partial^2 u}{\partial x^2} - \frac{4\pi i}{\lambda}\frac{\partial u}{\partial z} = 0$$

- Basis of laser wave optics
- Solutions display diffraction: e.g. laser cavities
- reinterpret as a position wavefunction of mass-energy

Gaussian Beam solutions



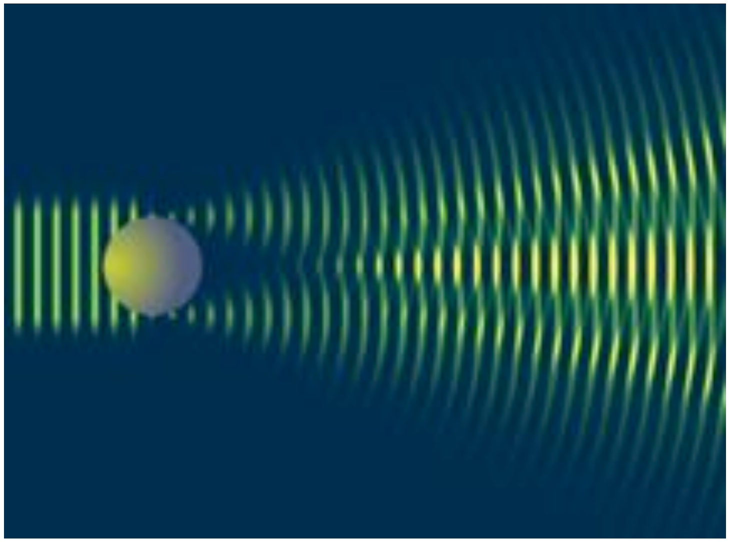
Rayleigh range and uncertainty of rays

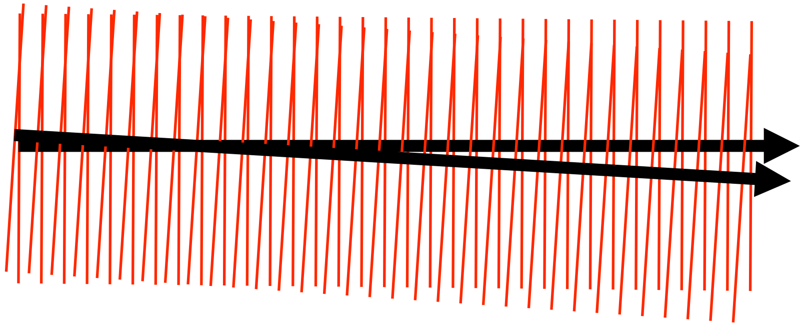


- Aperture *D*, wavelength λ *:* angular resolution λ/D
- Size of diffraction spot at distance *L: $L\lambda/D$*
- path is determined imprecisely by waves
- Minimum uncertainty at given *L* when aperture size =spot size, or

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

Indeterminacy of a Planckian path





- Classical spacetime manifold defined by paths and events
- path~ ray approximation of wave
- Indeterminacy of geometry reflects limited information content of band-limited waves

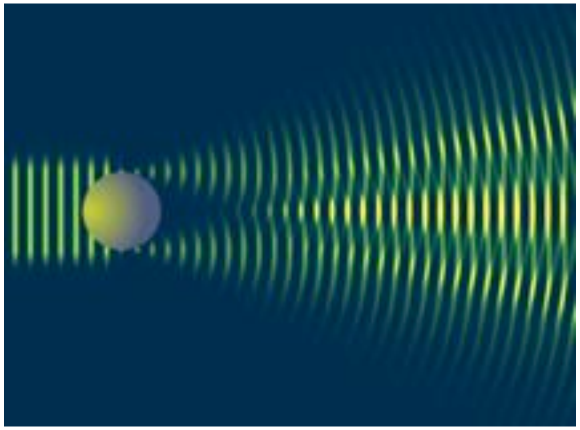
holographic approach to the classical limit

- 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:

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



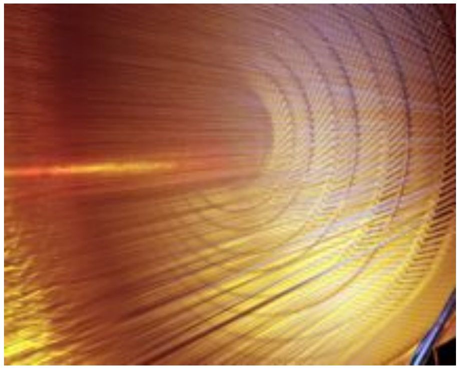
- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

Holographic Noise in Interferometers

- Nonlocality: uncertainty in relative transverse positions at km separation
- Fractional precision < 10^{-21}, > "halfway to Planck"
- Random variation in arm length difference appears in signal

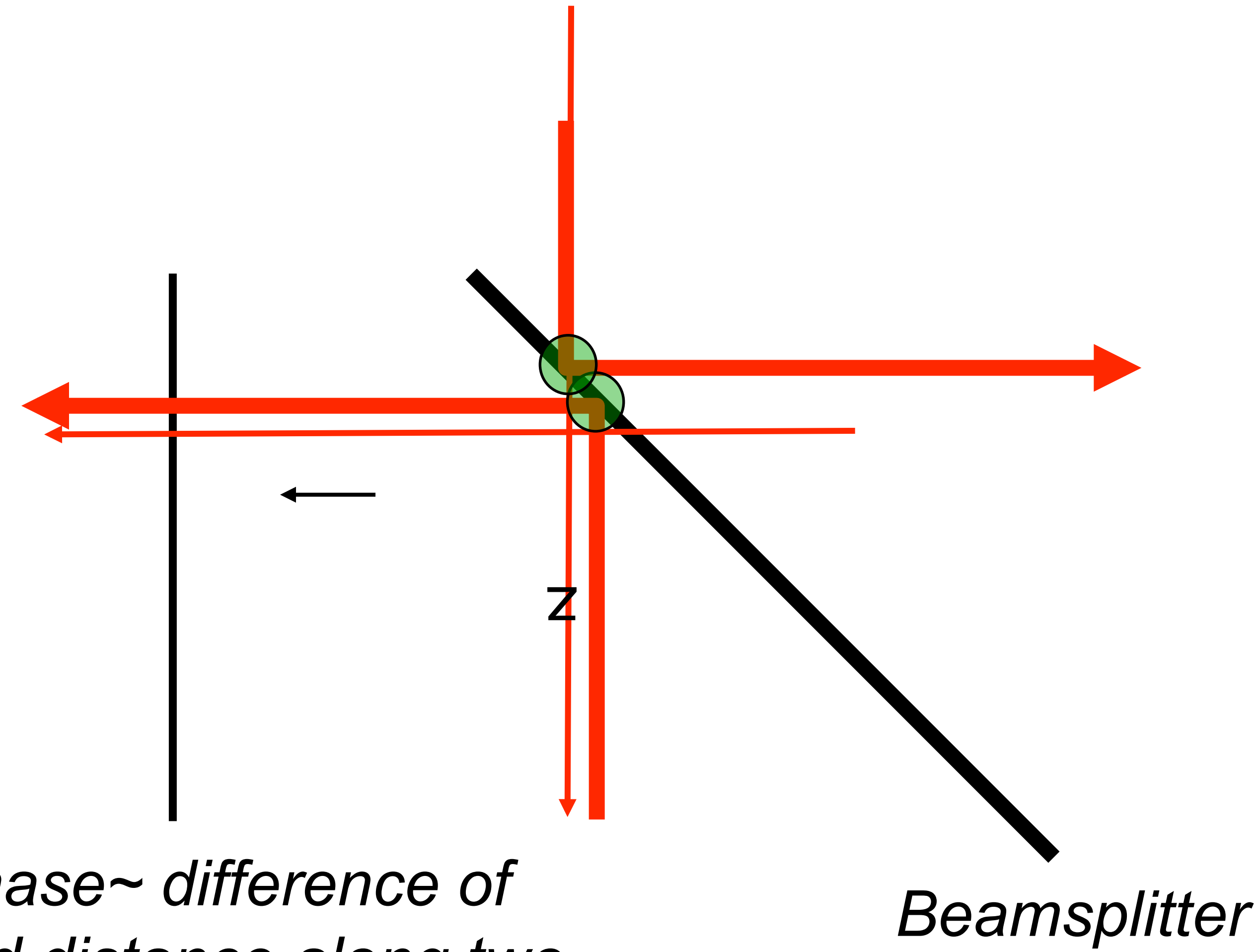
Measurement of holographic geometry requires coherent transverse position measurement over macroscopic distance

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



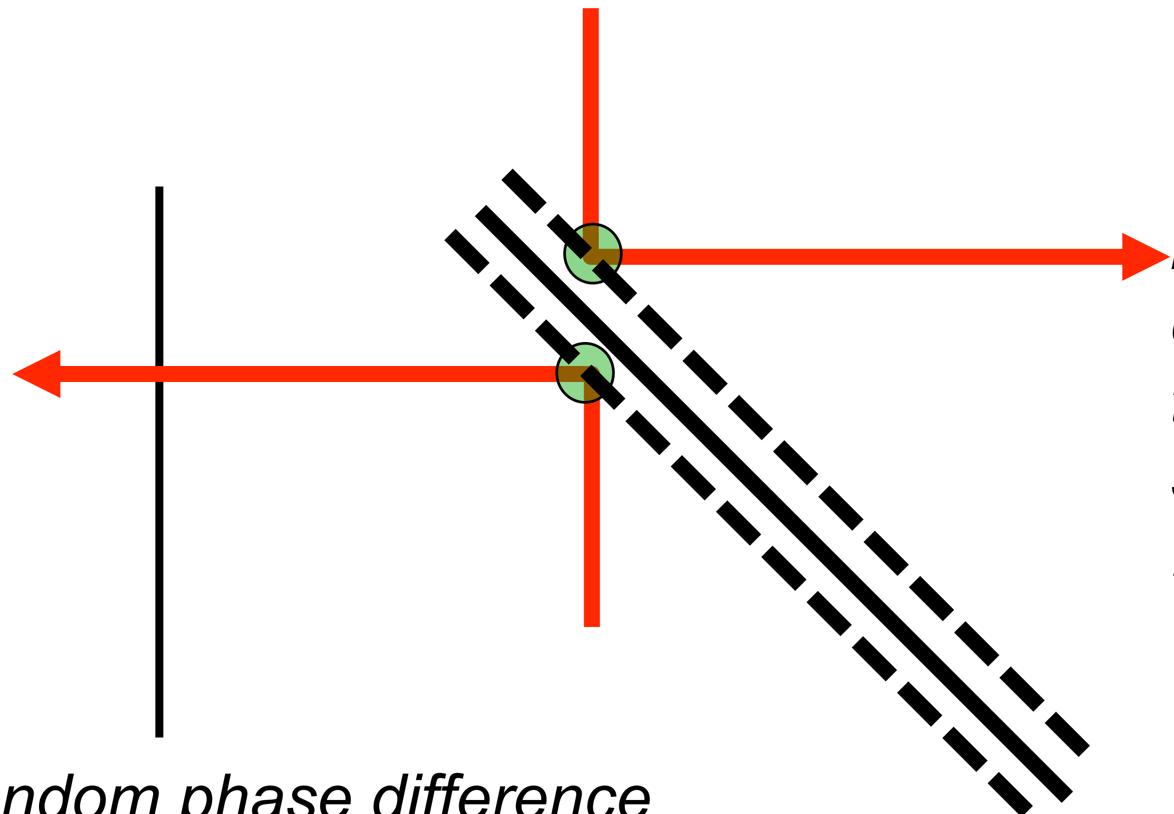
LIGO/GEO600: $\sim 10^{-18}$ m, over $\sim 10^{3}$ m

Beamsplitter and signal in Michelson interferometer



Signal phase~ difference of integrated distance along two orthogonal arms

Holographic noise in the signal of a Michelson interferometer

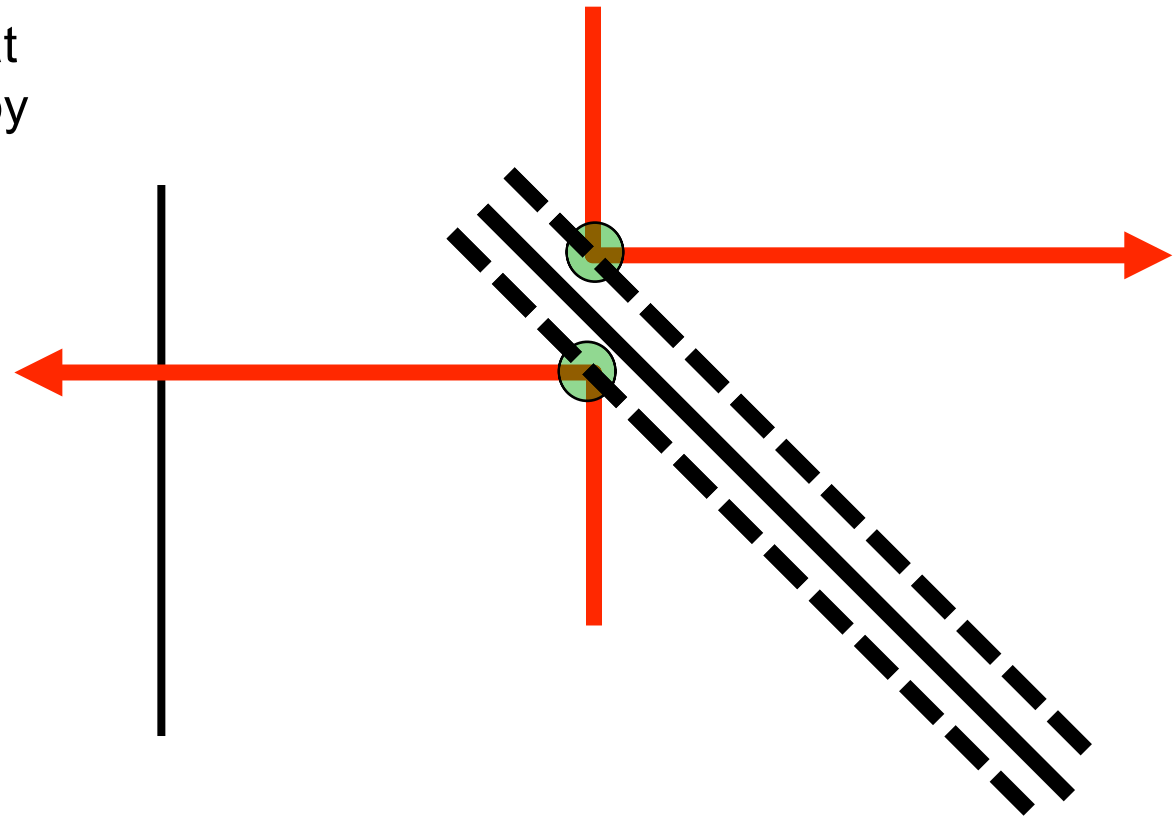


reflection events at two times separated by 2L/c

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

Holographic uncertainty of positions of beamsplitter

- Position wavefunction widths of beamsplittter at reflection events given by Gaussian beamwidth



- apparent arm length difference is a random variable, with variance

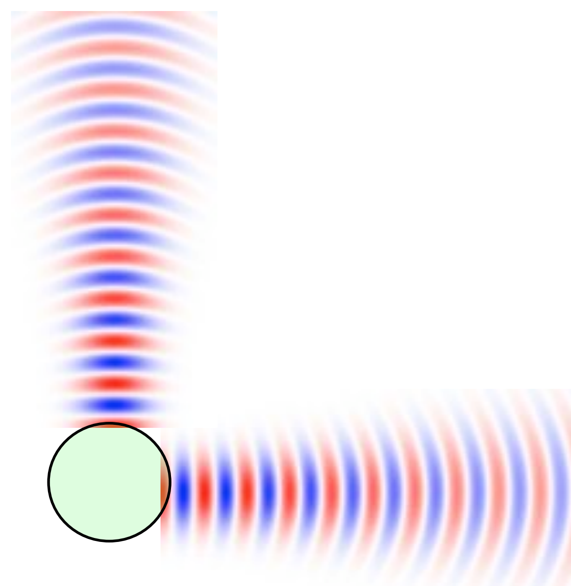
$$L\lambda / \pi$$

this is a new effect predicted with no parameters

Wavefunction and wavefronts

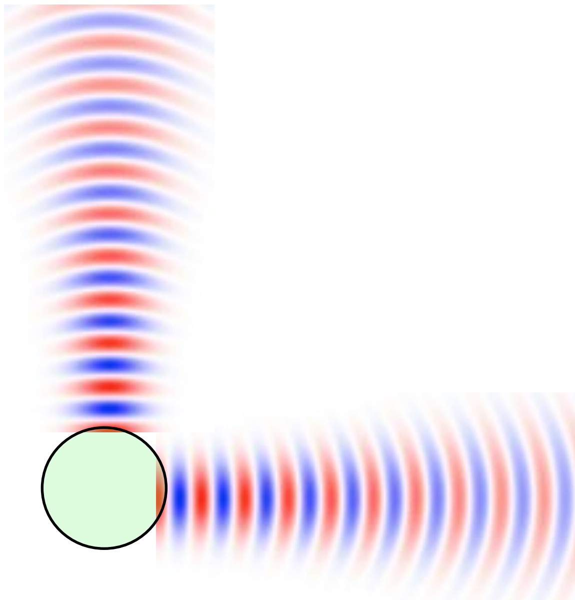
In an optical cavity of any size, the holographic transverse uncertainty is smaller than the beam waist by a factor

$$\sqrt{\lambda_P / \lambda_{laser}}$$



Interferometer with Planck radiation

- Beamsplitter mass limited to Planck surface density
- No “better measurement” of position is possible



Power Spectral Density of Shear Noise

dimensionless shear

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

At f=c/2L, shear fluctuations with power spectral density

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

Universal Holographic Noise

*flat power spectral density of **shear** perturbations:*

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

- general property of holographic quantum geometry
- spectrum with no parameters
- spatial shear character: different from strain
- Definitively falsifiable
- Amplitude spectral density of equivalent strain, at low frequencies in folded Michelson interferometers:

$$h(f) = \mathcal{N}^{-1}\sqrt{\Phi/L^2} = \mathcal{N}^{-1} 2\sqrt{t_P/\pi} = \mathcal{N}^{-1} 2.6 \times 10^{-22}/\sqrt{\mathrm{Hz}}$$

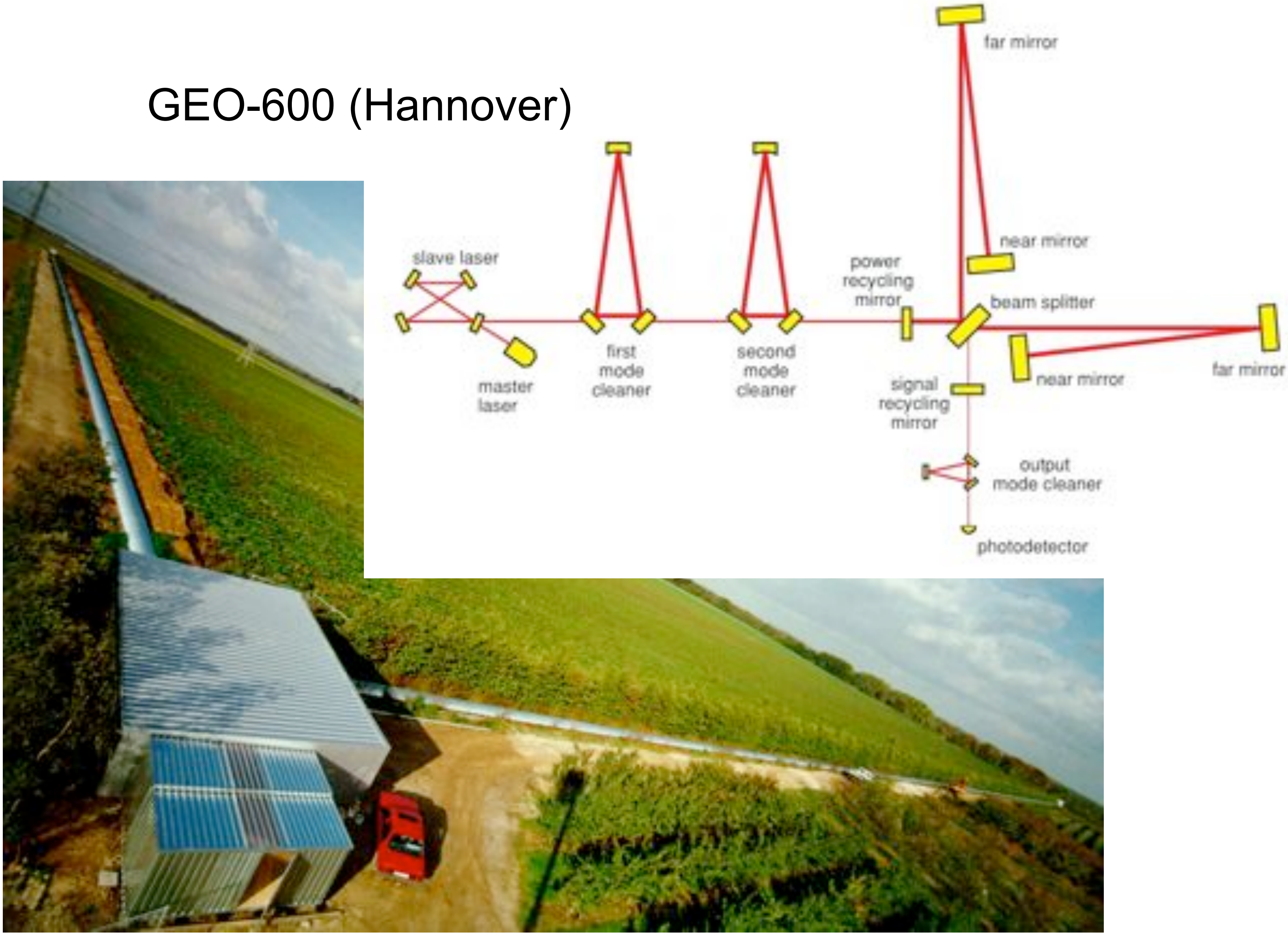
Holographic noise does not carry energy

- flat space, no metric perturbations
- Perturbation in relative position of massive bodies, "movement without motion"
- ~sampling or pixelation noise, not thermal noise
- Bandwidth limit of spacetime relationships
- Necessary so the number of distinguishable position states does not exceed holographic bound on degrees of freedom
- No curvature
- no strain, just shear

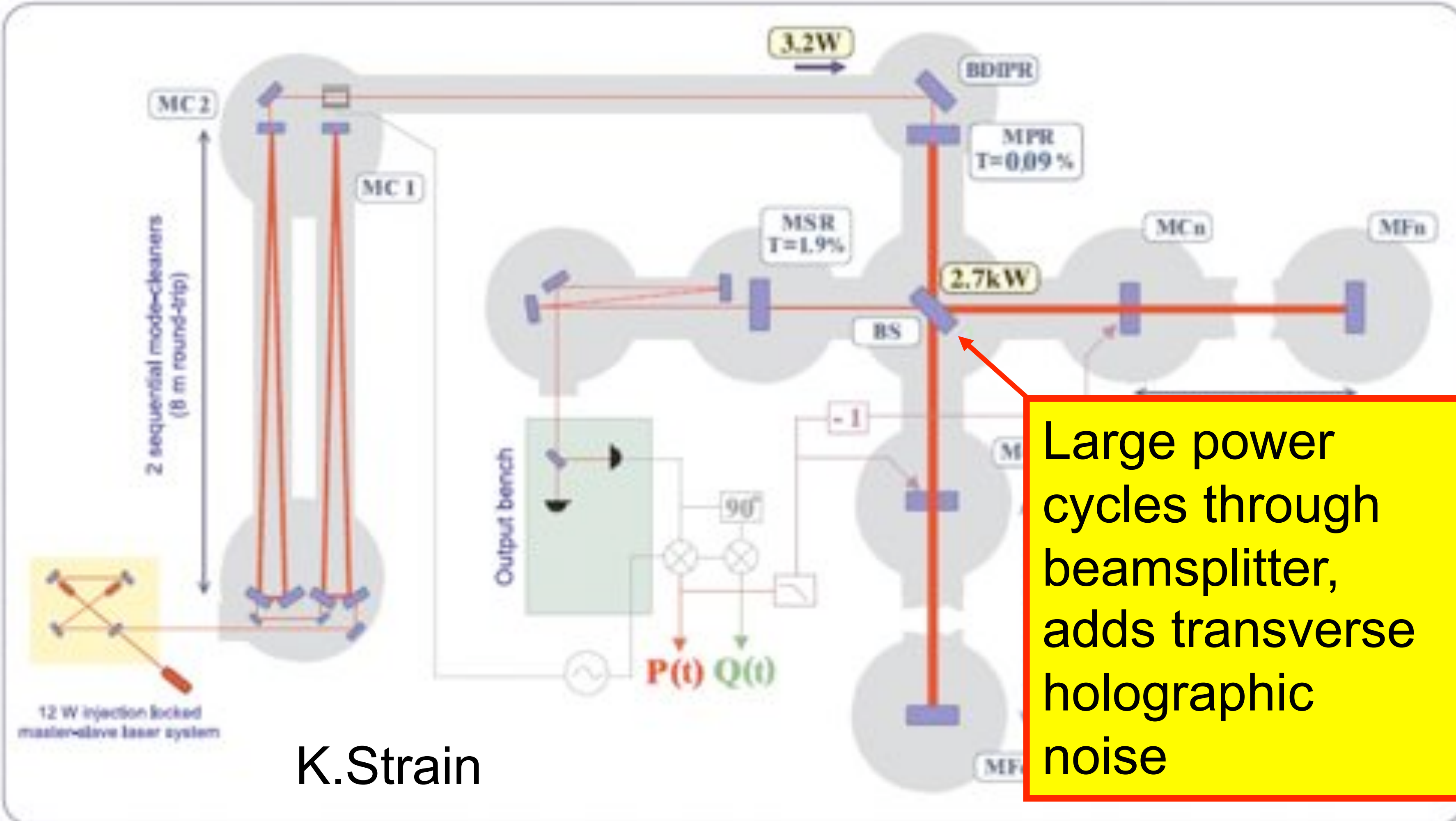
Response of an interferometer

- Shear not strain: different from gravitational waves
- Folded arms sensitive to strain not shear
- GEO600 is better than LIGO
- Mimics bounded random walk of beamsplitter

GEO-600 (Hannover)



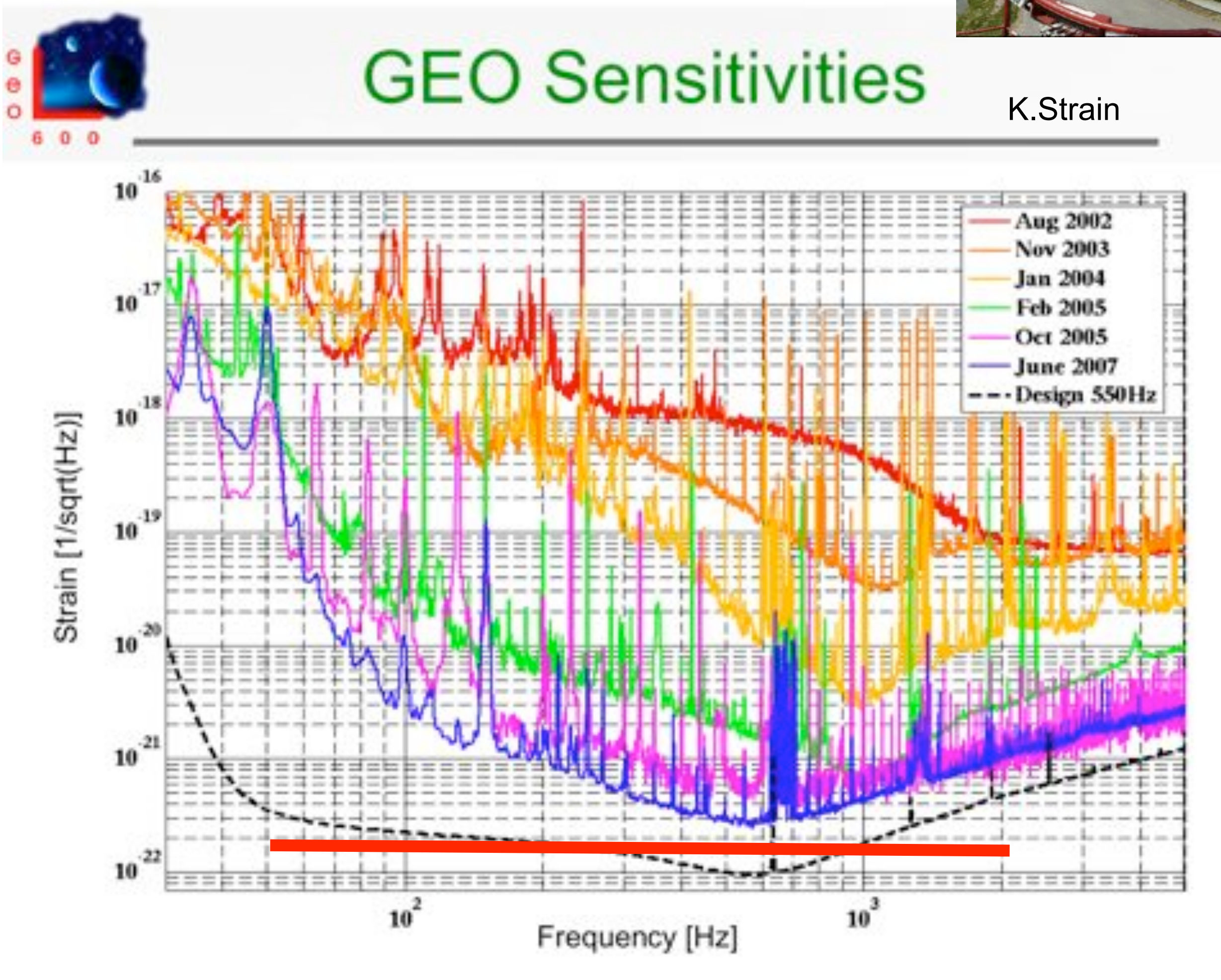
The GEO600 Interferometer



Large power cycles through beamsplitter, adds transverse holographic noise

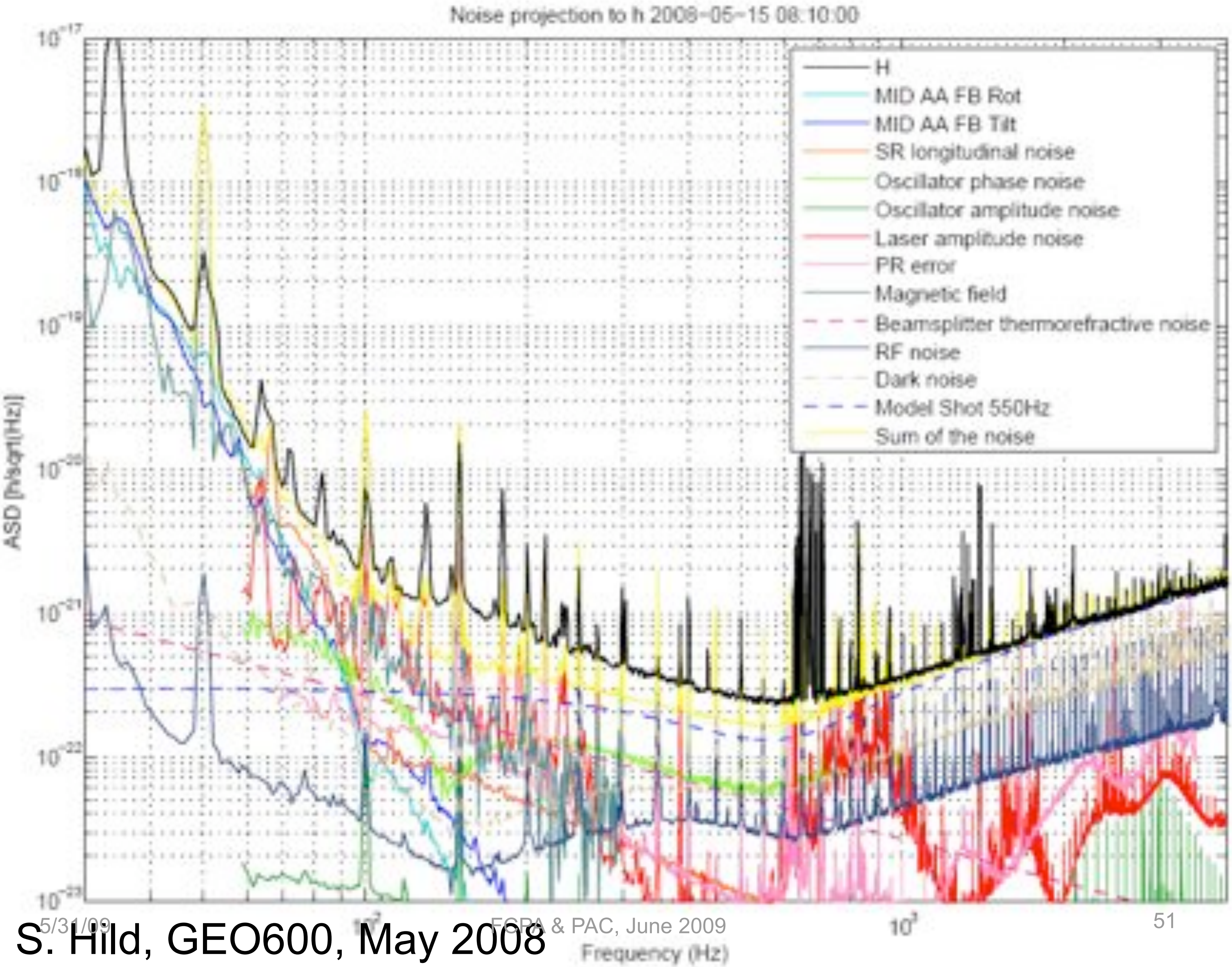
K.Strain

Noise in GEO600 over time

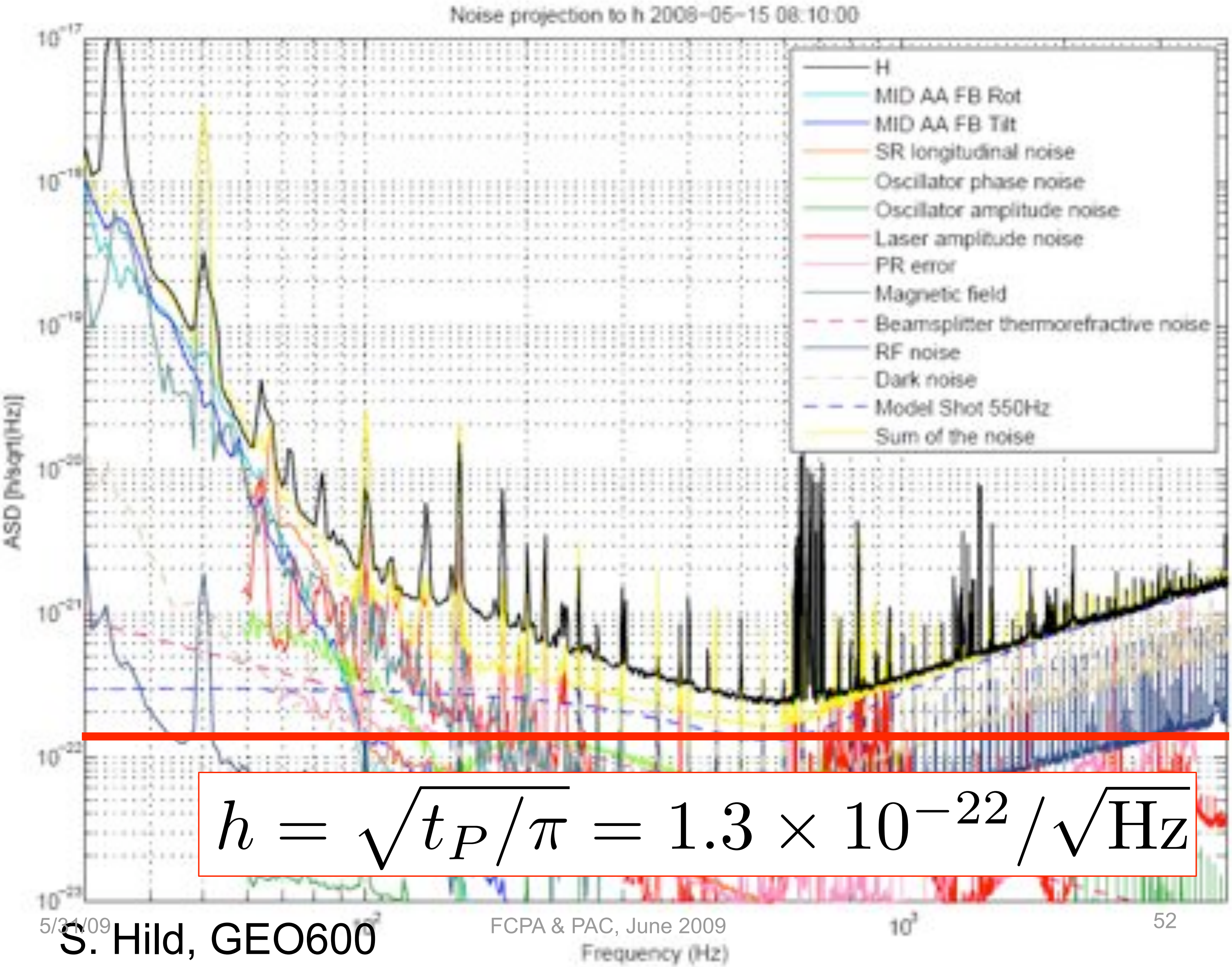


K.Strain

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



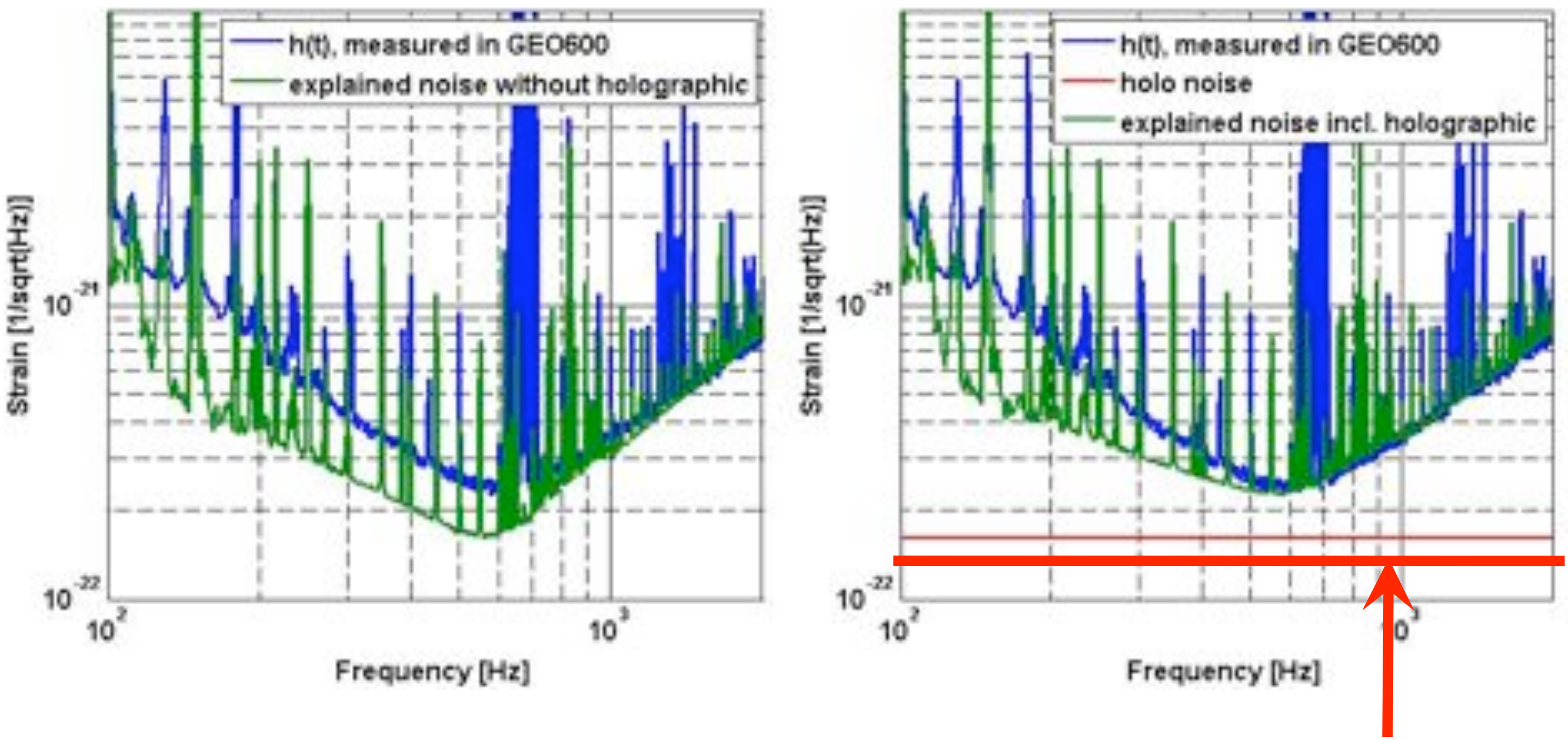
S. Hild, GEO600, May 2008



$$h = \sqrt{t_P/\pi} = 1.3 \times 10^{-22}/\sqrt{\mathrm{Hz}}$$

S. Hild, GEO600

“Mystery Noise” in GEO600



$$\sqrt{t_{Planck} / \pi}$$

Data: S. Hild (GEO600)

Prediction: CJH, arXiv:0806.0665
(Phys Rev D.78.087501)

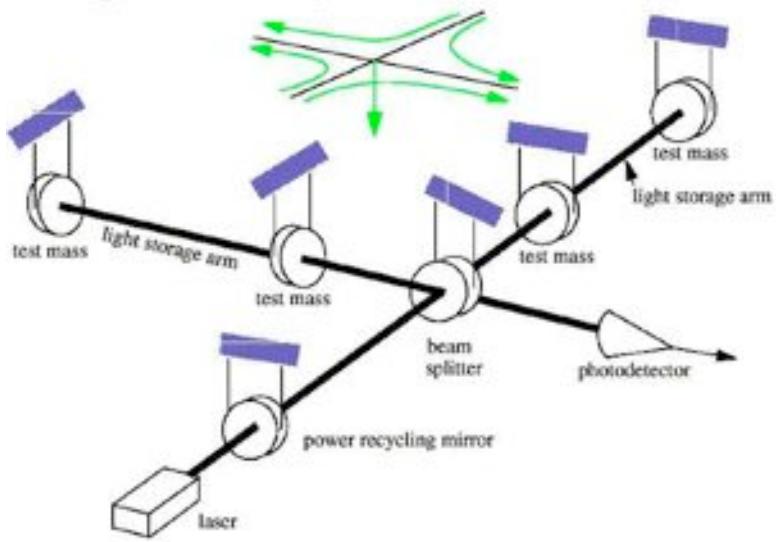
zero-parameter prediction for holographic noise in GEO600 (equivalent GW strain)

Total noise: not fitted

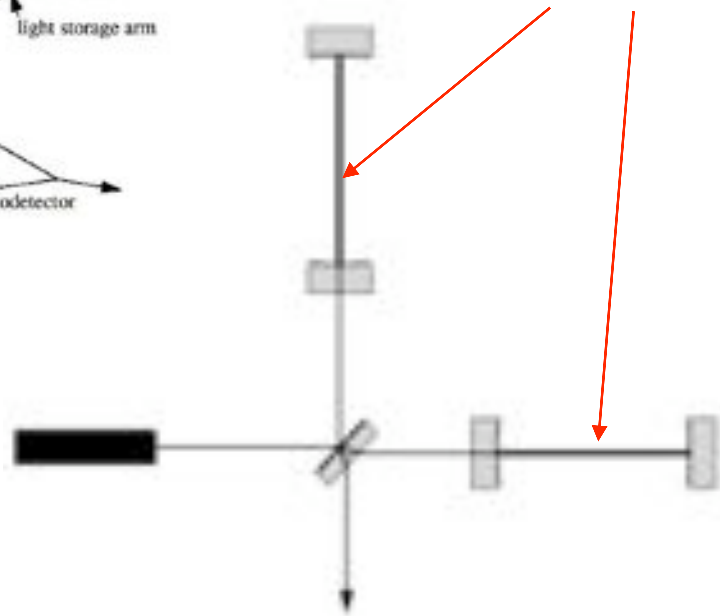
Why doesn't LIGO detect holographic noise?

- LIGO design is not as sensitive to transverse displacement noise as GEO600
- relationship of holographic to gravitational wave depends on details of the system layout

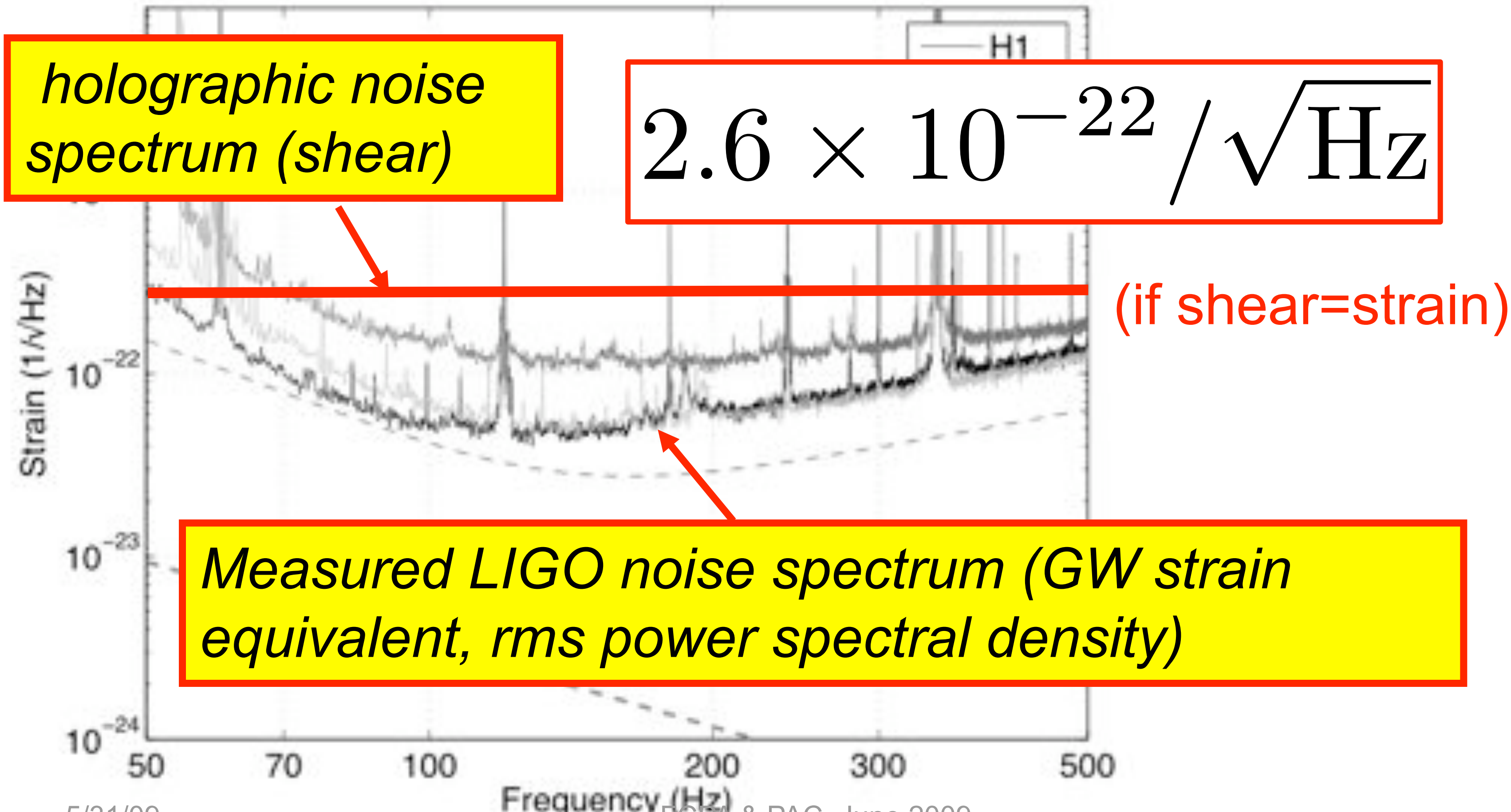
Fig. 1. Schematic layout of a LIGO interferometer.



Shear motion is not amplified in FP cavities

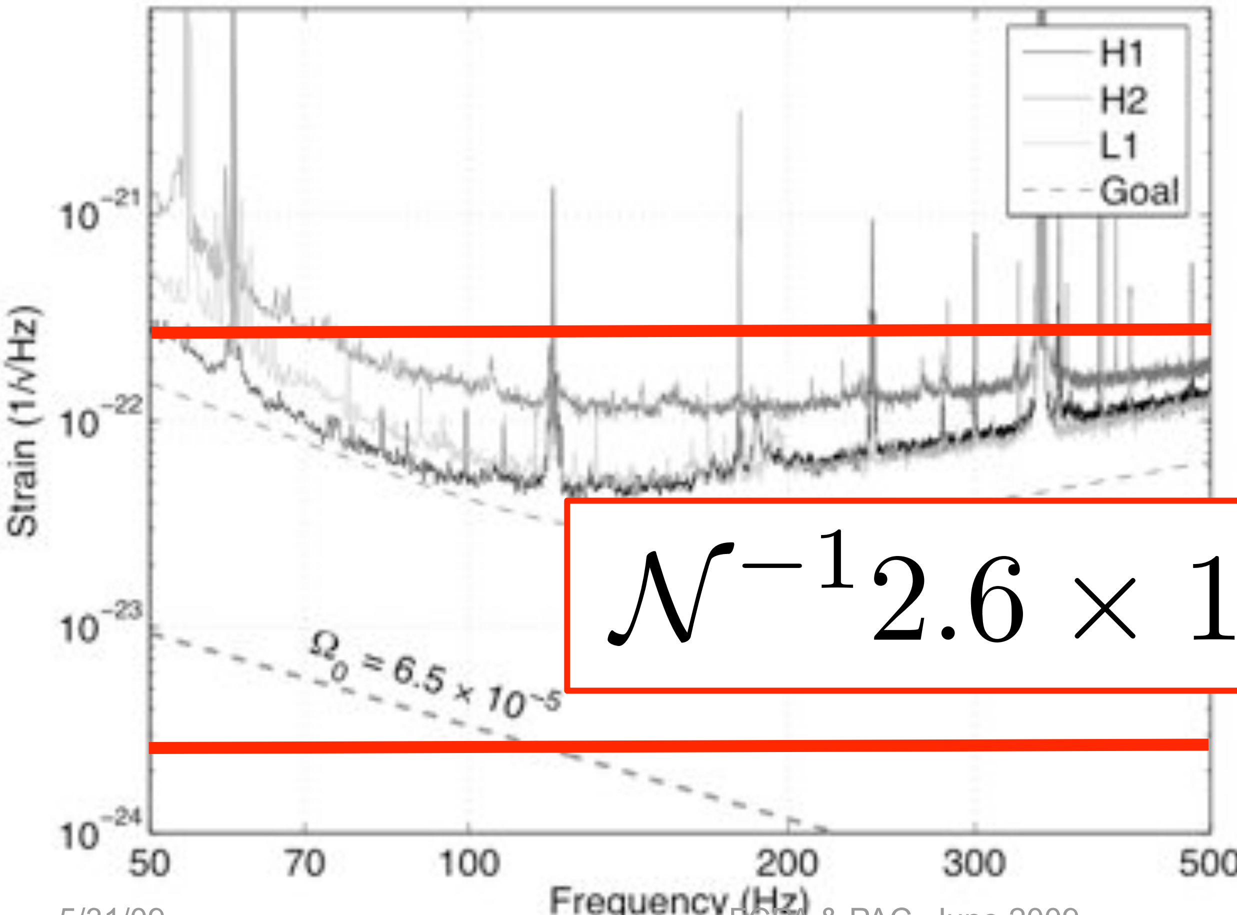


LIGO noise (astro-ph/0608606)



holographic noise prediction for LIGO: reduced by ~arm cavity finesse

$$\mathcal{N}^{-1} 2\sqrt{t_P/\pi}$$



$$\boxed{\mathcal{N}^{-1} 2.6 \times 10^{-22}/\sqrt{\mathrm{Hz}}}$$

about 100 times less

Interferometers can detect quantum indeterminacy of holographic geometry

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

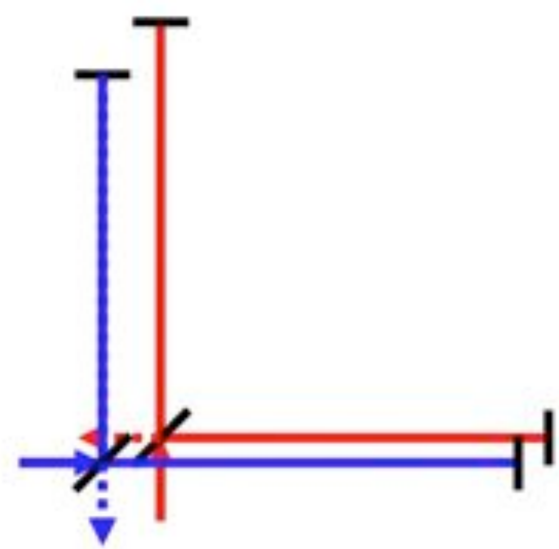
CJH: Phys. Rev. D 77, 104031 (2008); **arXiv:0806.0665**
CJH, **arXiv:0905.4803**

Current experiments: summary

- Most sensitive device, GEO600, sees noise compatible with holographic spacetime indeterminacy
- GEO600 paper in preparation
- GEO600 is operating at holographic noise limit
- LIGO: current system not sensitive enough
- LIGO H1/H2 correlation: almost there, ambiguous result
- No experiment has been designed to look for holographic noise
- A definitive result is not possible with LIGO or GEO600
- Proof: new apparatus, coherence of adjacent systems

Dedicated holographic noise experiments: beyond GW detectors

- f ~100 to 1000 Hz with GW machines
- f ~ 3 MHz possible with new apparatus on ~40m scale
- Easier suspension, isolation, optics, vacuum, smaller scale
- Correlated holographic noise in adjacent paths: signature of holographic effect

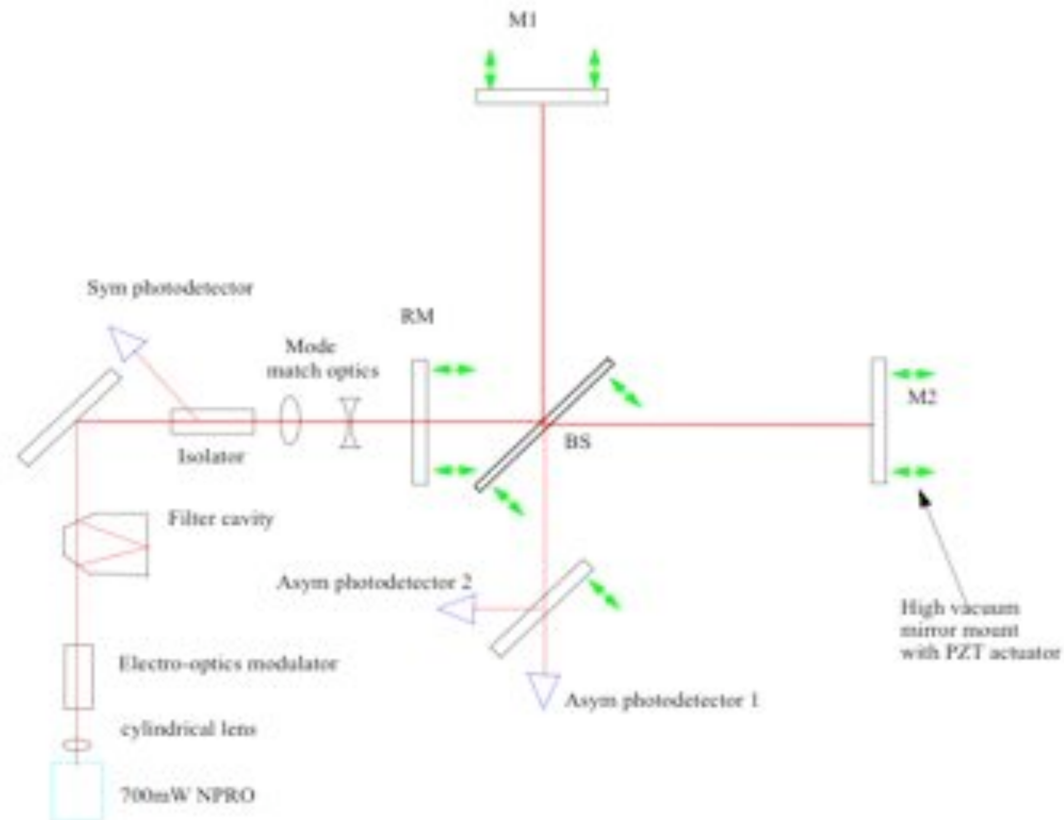


Conceptual Design from Rai Weiss

Two ~40m Michelson interferometers in coincidence

~1000 W cavity

holographic noise= laser photon shot noise in ~5 minutes (1 sigma)



Goals of the Fermilab Holometer R & D project

- Measure the spatial cross correlation of shear noise to Planck precision
- Design apparatus to provide convincing evidence for universal Planckian shear noise, or an upper limit to constrain holographic theories

Status of the Fermilab Holographic Interferometer

- Team so far: Fermilab (CJH, Chou, Wester, Steffen, Ramberg, Stoughton, Tomlin, Ruan, Bhat), MIT (Weiss, Waldman), Caltech (Whitcomb), UC (Meyer), UMich (Gustafson)
- Meyer & Chou: UC/FNAL collaborative proposal
- Building tabletop prototype
- Weiss concept for correlated interferometers
- Sites at FNAL or off site available and surveyed: ~40m arms possible, seismically acceptable
- Invited to make PAC presentation
- External advice: AEI Hannover, AEI Golm, U. Glasgow
- Hannover Workshop (May 19-20, 2009)
- Likely Hannover followup experiment in 2010

What we are asking for

- Blessing to proceed with R & D immediately
- Resources: parts, labs, engineering
- Funding for construction of full system in FY10/11

Science of Holographic Noise

- If it is detected:
  - Measure fundamental interval of time
  - Measure all physical degrees of freedom: explore physics “from above”
  - Study holographic relationship between spacetime and mass-energy, emergence of spatial dimensions
  - Precisely compare noise spectrum with Planck time derived from Newton’s *G:* test fundamental theory
  - Test predictions for spectrum, spatial correlations: properties of holographic geometry

Holographic modes: clue to new dark energy physics?

- Holographic blurring is ~0.1mm at the Hubble length
- ~(0.1mm)^-4 is the dark energy density
- “Nonlocality length” for dark energy is holographic displacement uncertainty, scaled to Hubble length
- (literature on “holographic dark energy” centers on same numerology)
- Does not “explain” dark energy!