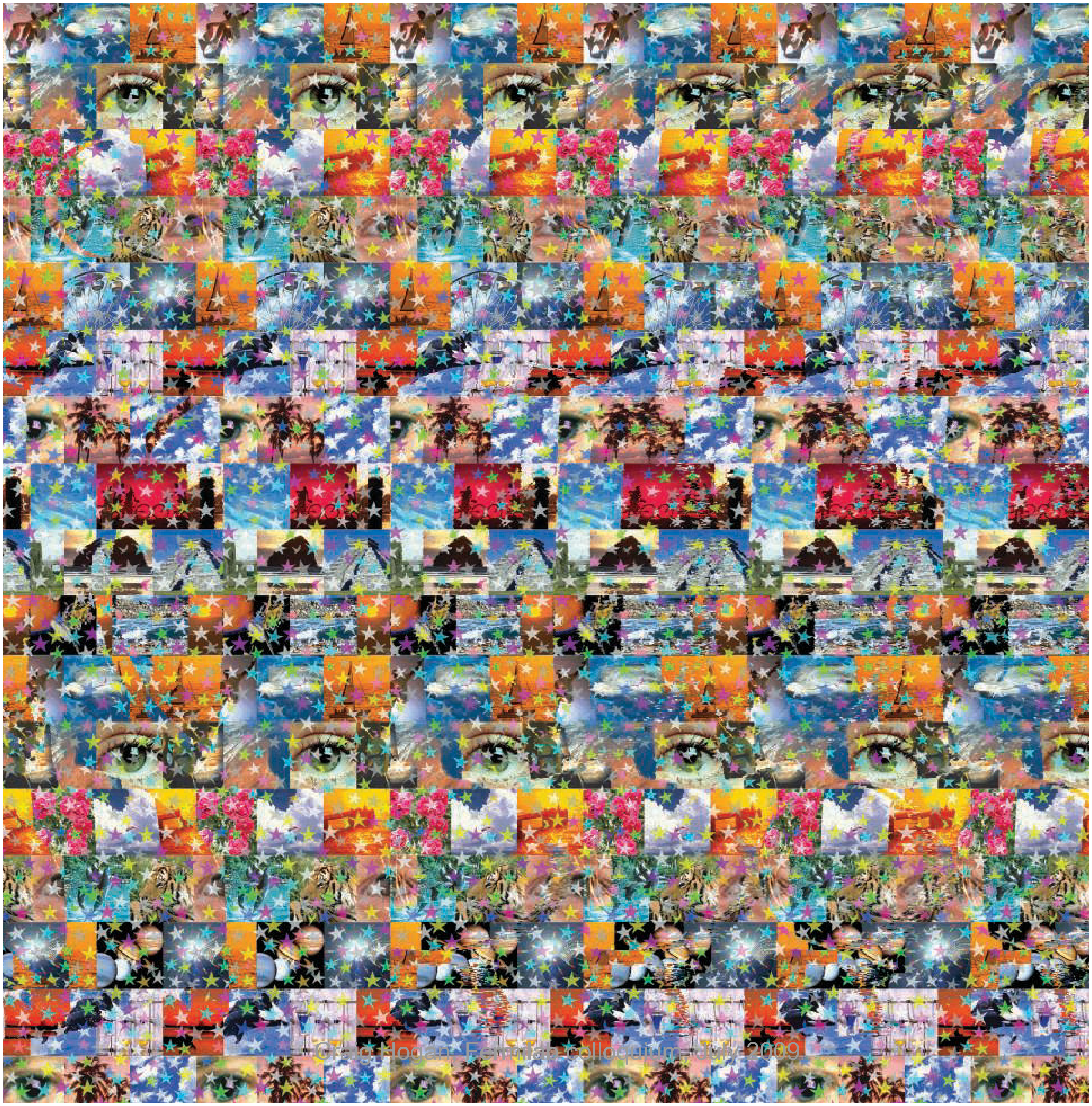


Craig Hogan, Fermilab colloquium, July 2009

Holographic Noise in Interferometers

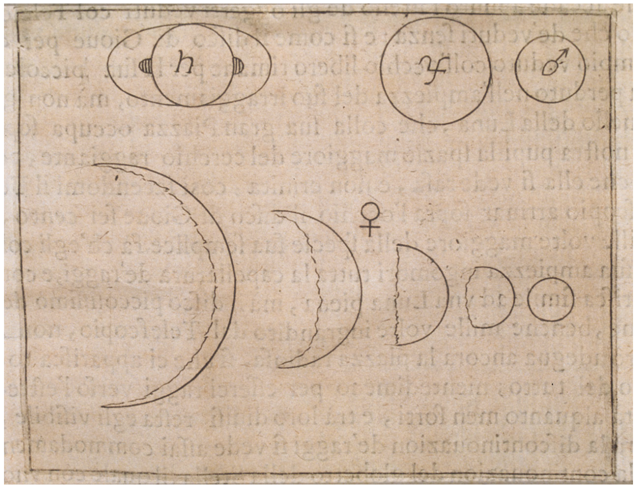
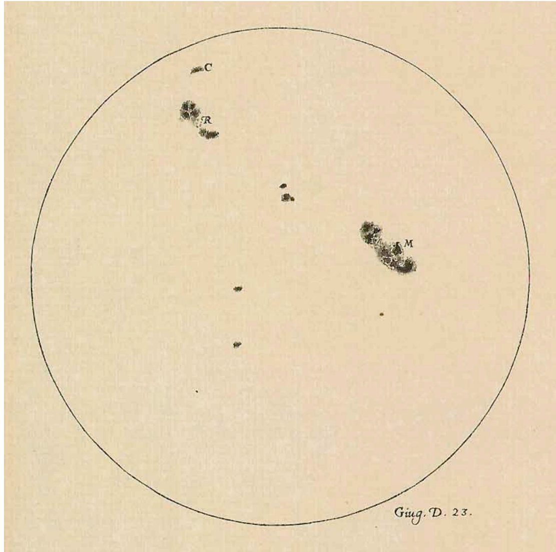
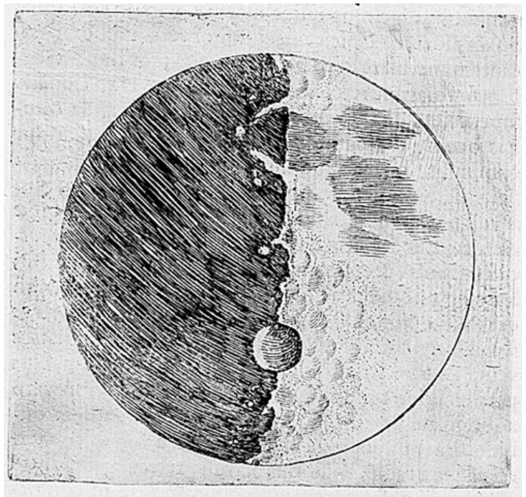
A new experimental probe of Planck scale unification

Craig Hogan

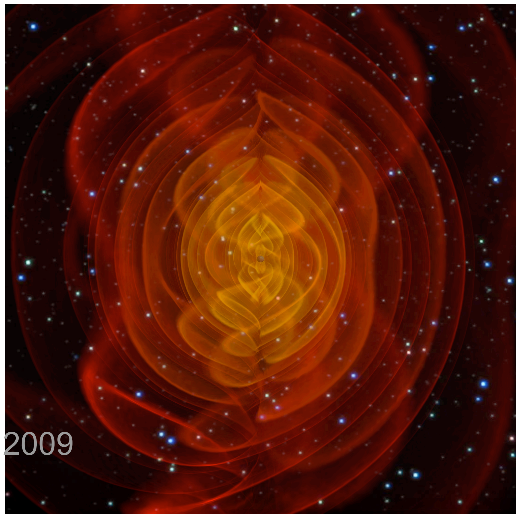
Fermilab and the University of Chicago

How often does science explore something really new?

- 400 years ago: Galileo’s telescope

- Today (soon!): gravitational waves

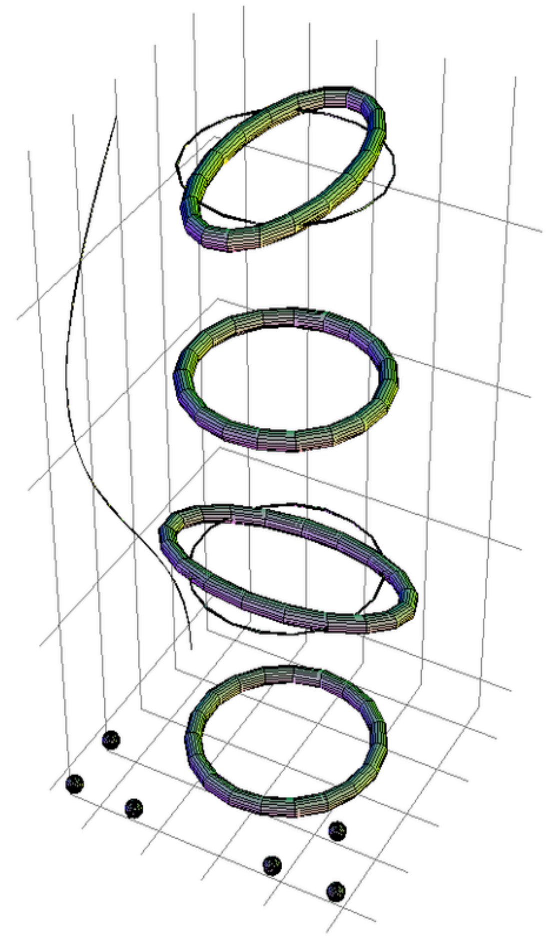


Gravitational Waves: a New Science

- Telescopes extend the human sense of sight
- Gravitational wave detectors extend hearing
- Light: electromagnetic radiation from accelerating particles
- Gravitational radiation: spacetime vibrations from accelerating mass-energy
- (Not the main subject of this talk!)

Gravitational waves: Spacetime Vibrations

- Caused by motions of mass and energy
- Waves are detected by their effect on distance between bodies



Gravitational waves are hard to detect

- Even with large energy, distortions of spacetime by faraway motions are very small
- fractional stretching of distance in plane of wave:

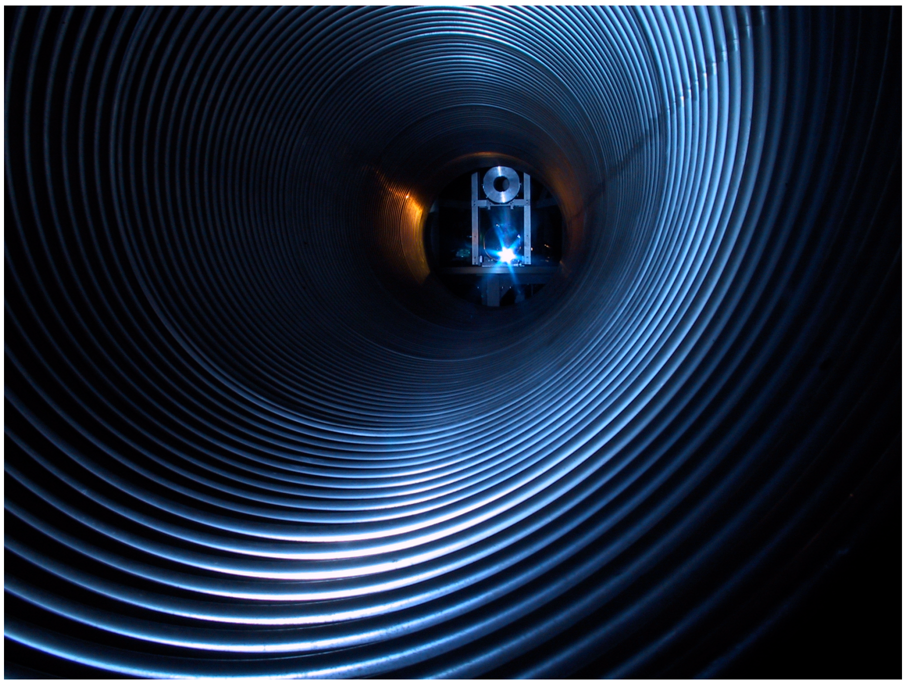
$$h = \Delta L / L \approx (GM / Rc^2)^2 (R / D)$$

R= size, *D*= distance, *M*= mass, *h*= dimensionless strain amplitude

- Pattern, frequency correspond to projection of time-varying quadrupole moment of distant source
- Strong sources have frequencies <1000 Hz
- Requires a new technology that is now maturing: interferometry

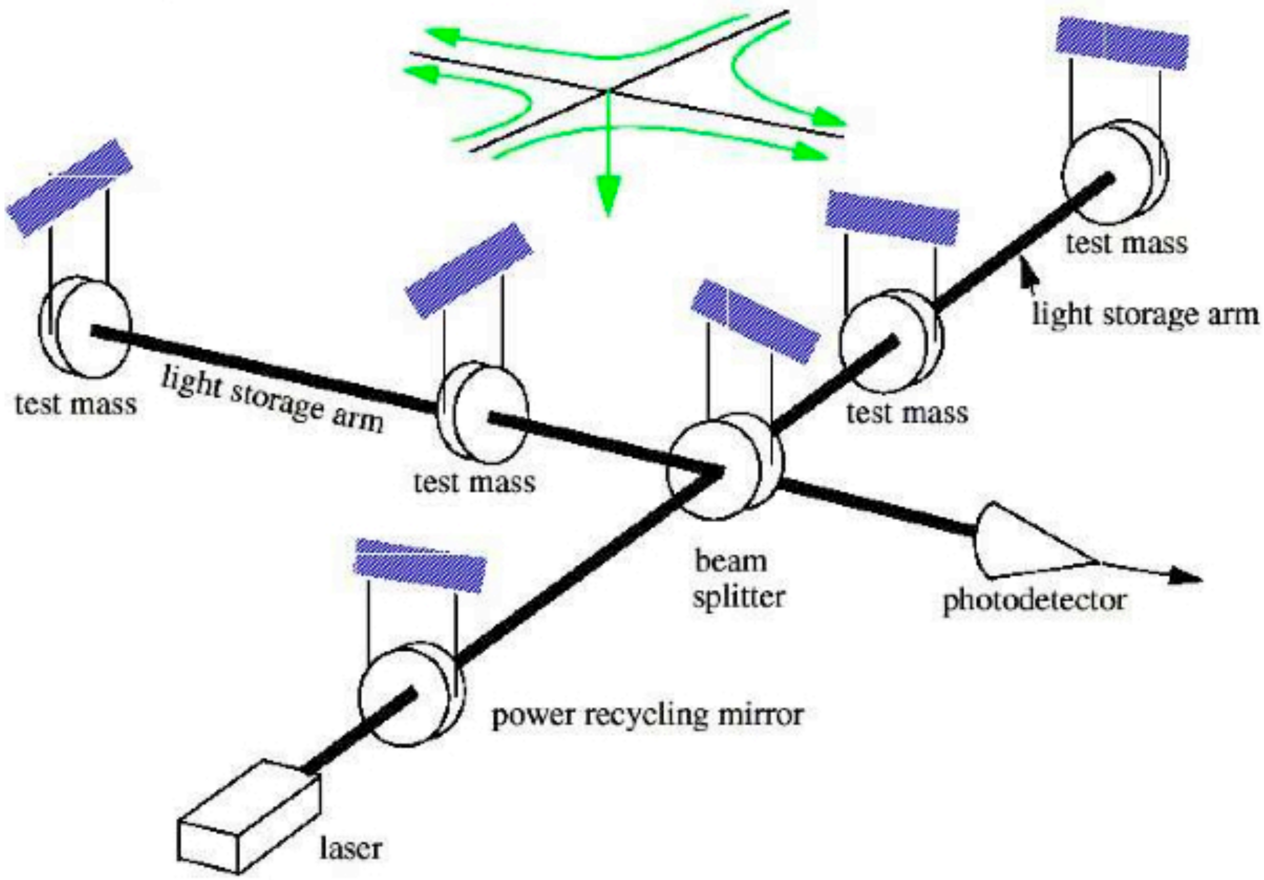
New technology of interferometers

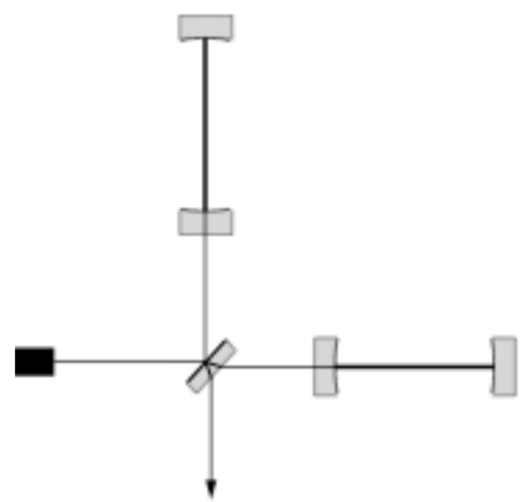
LIGO/GEO600: Relative positions of massive bodies now measured to $\sim 10^{-18}$ m, over a distance of $\sim 10^{3}$ m



Supersensitive microphones: interferometers measure subatomic motions over large distances

Fig. 1. Schematic layout of a LIGO interferometer.





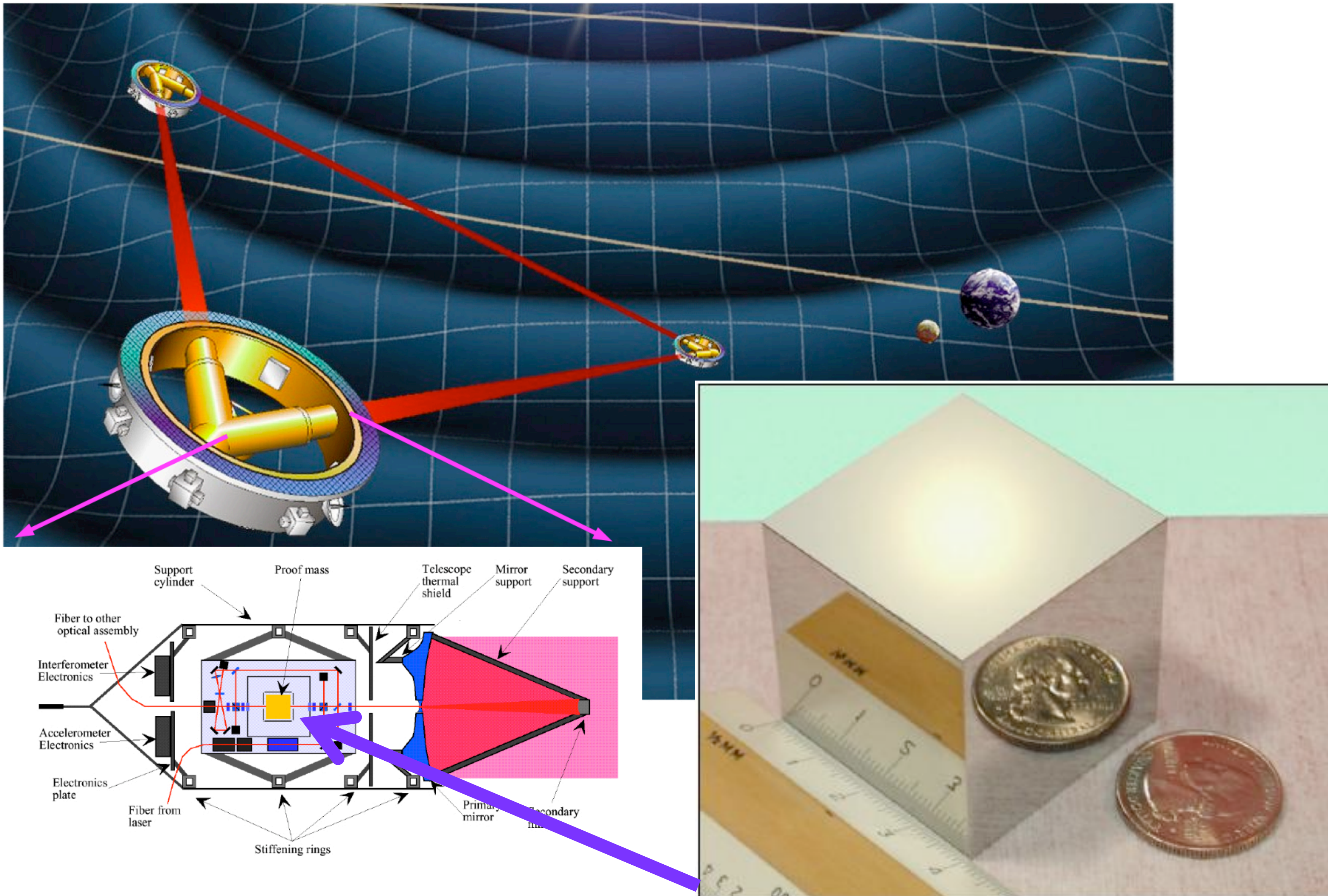
GEO-600 (Hannover, Germany)

LIGO: Hanford, WA and Livingston, LA

audio frequencies (10 to 1000 Hz)

Last gasps (minutes) of dying stars:
neutron stars, black holes, supernovae

Future LISA mission: 5 million kilometers, ultra bass notes (mHz)



Interferometers might also probe new unification physics

- Spacetime is measured using mass-energy
- Interferometers measure macroscopic distances between masses (mirrors) to very high precision
- may sense new physics of unification, not just gravity
- Not the same as gravitational waves

Unification: relationship of spacetime to the stuff within it

- Standard physics:
  - Mass-energy quantum particles/waves move in spacetime, follow metric
  - Spacetime curves in response to mass-energy
  - Spacetime is smooth, infinitely divisible
- New physics of unification:
  - Spacetime and mass-energy both emerge from something different (strings, matrices,…?)
  - At some small scale, they blend together
  - Under extreme magnification, spacetime no longer looks like spacetime
  - there is a minimum time/ maximum frequency

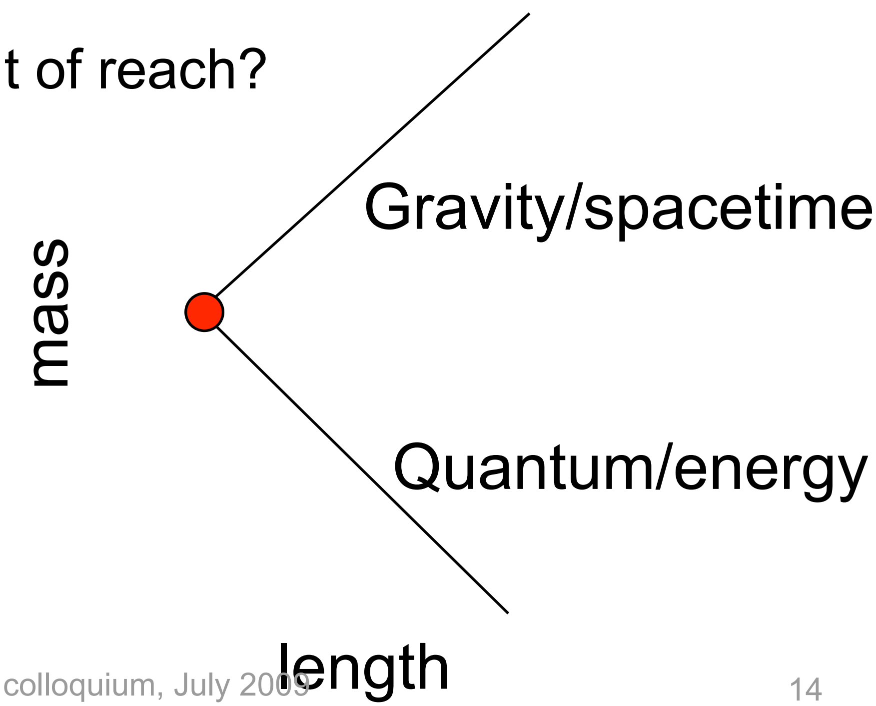
Planck scale: spacetime merges with mass-energy

- Quantum gravity suggests a minimum (Planck) time,

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

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

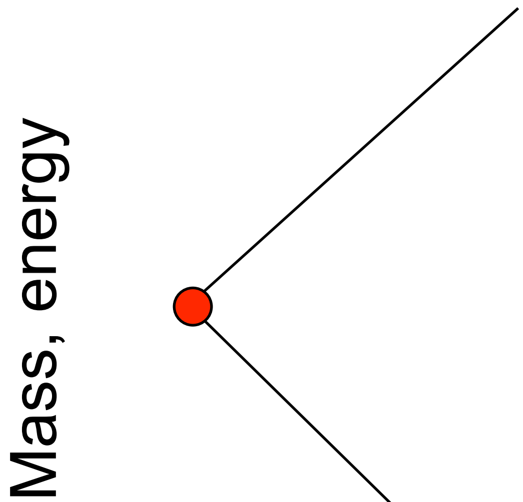
- ~ particle energy 10^{16} TeV: out of reach?

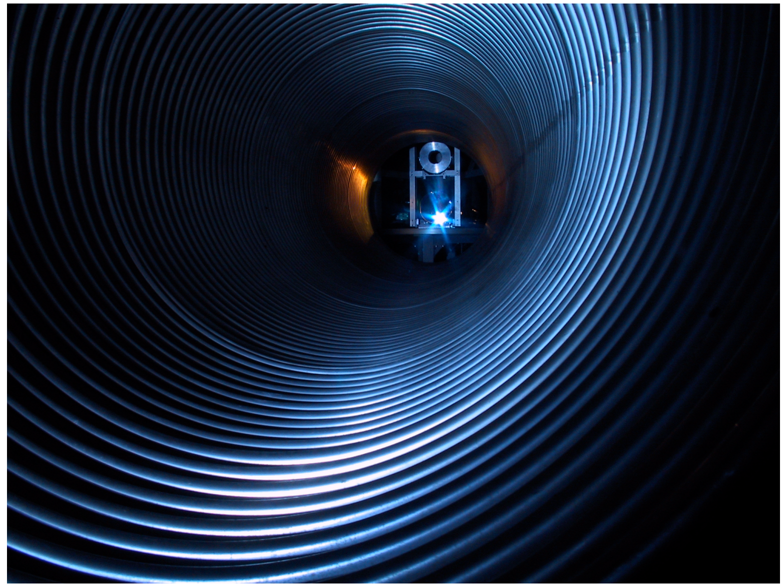


Consequences of a minimum time/maximum frequency

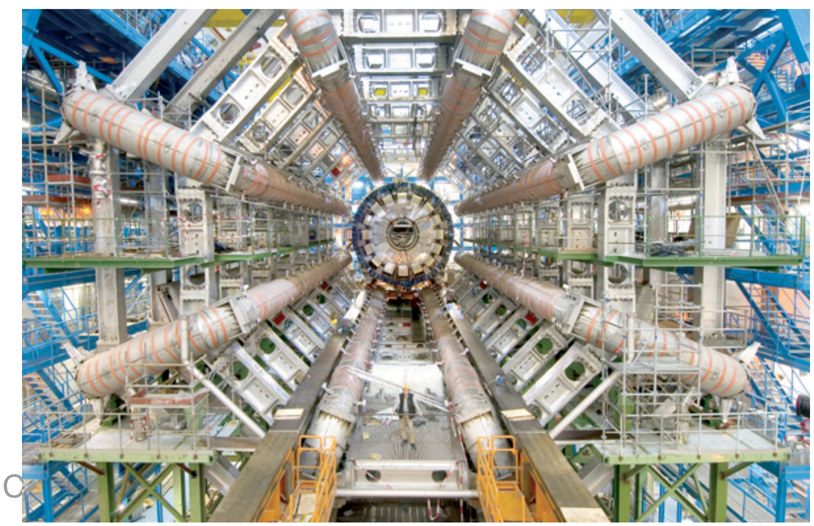
- Old idea: “quantum foam”, breakdown of physics with a UV cutoff at the Planck scale
- New idea: bandwidth limit of reality
- Nature: the ultimate internet service provider
- Shannon/Nyquist sampling theorem: any function with a maximum frequency is completely specified by two numbers per wavelength
- limit on relationship of one place to another: Planck carrier wave
- Consequences more radical than quantum foam localized at the Planck scale

Two approaches to the Planck scale





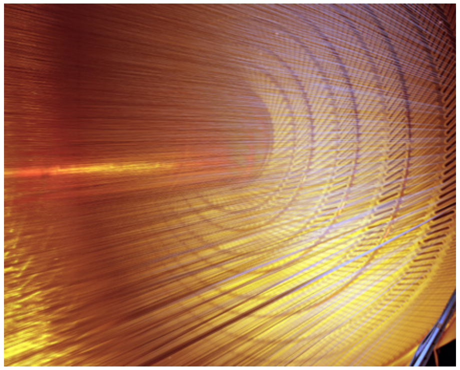
position

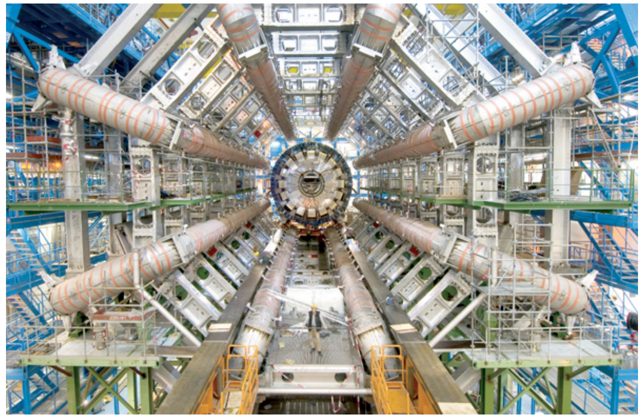


momentum

Two technologies: small things vs precision distances

CERN/Fermilab: TeV^{-1}~10^{-18} m: particle interactions





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

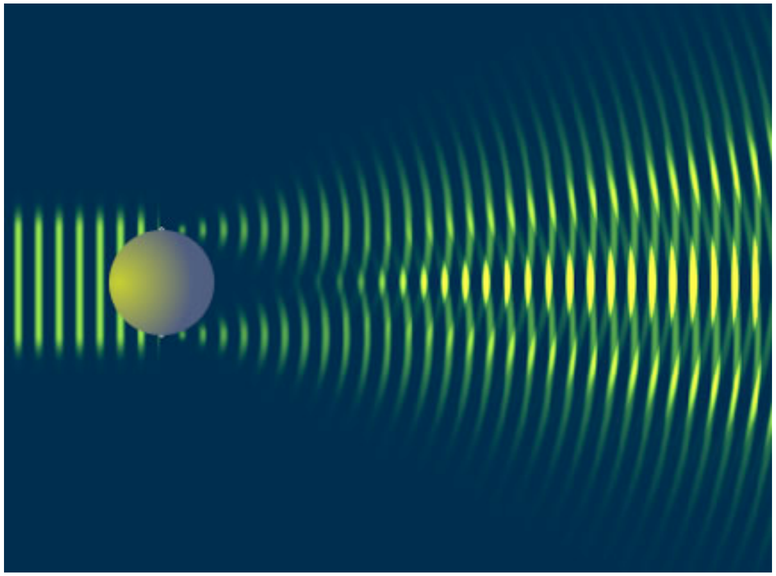
A new phenomenon?: holographic noise

- The Planck limit may affect interferometers
- uncertainty much larger than Planck scale in a particular interpretation of unification
- New universal random jitter: “Holographic Noise”
- This is not gravitational radiation: no metric distortion
- Instead, a time-varying violation of the equivalence principle

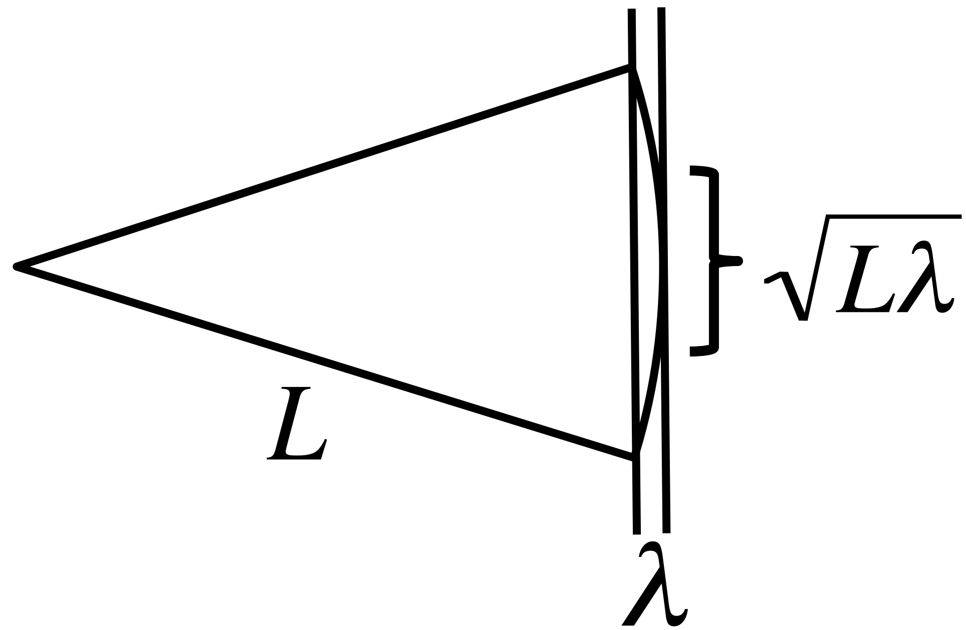
“Planck diffraction limit” at *L*

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

is >> Planck length



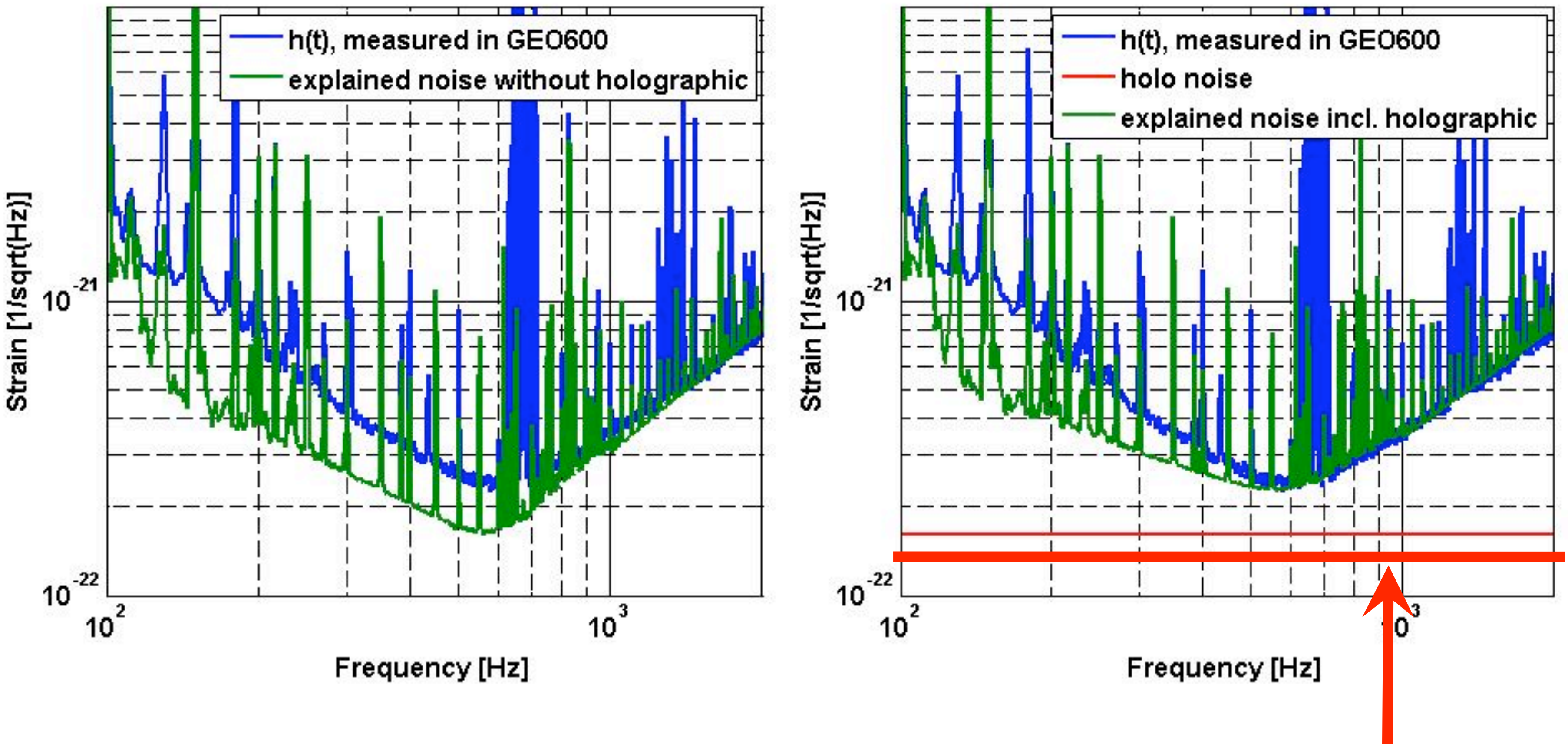
Planck frequency limit causes larger scale indeterminacy: transverse position wavefunction at longitudinal distance L



phase change in Planck wavefront spans a much larger transverse distance

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

- Interpretation of holographic unification 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

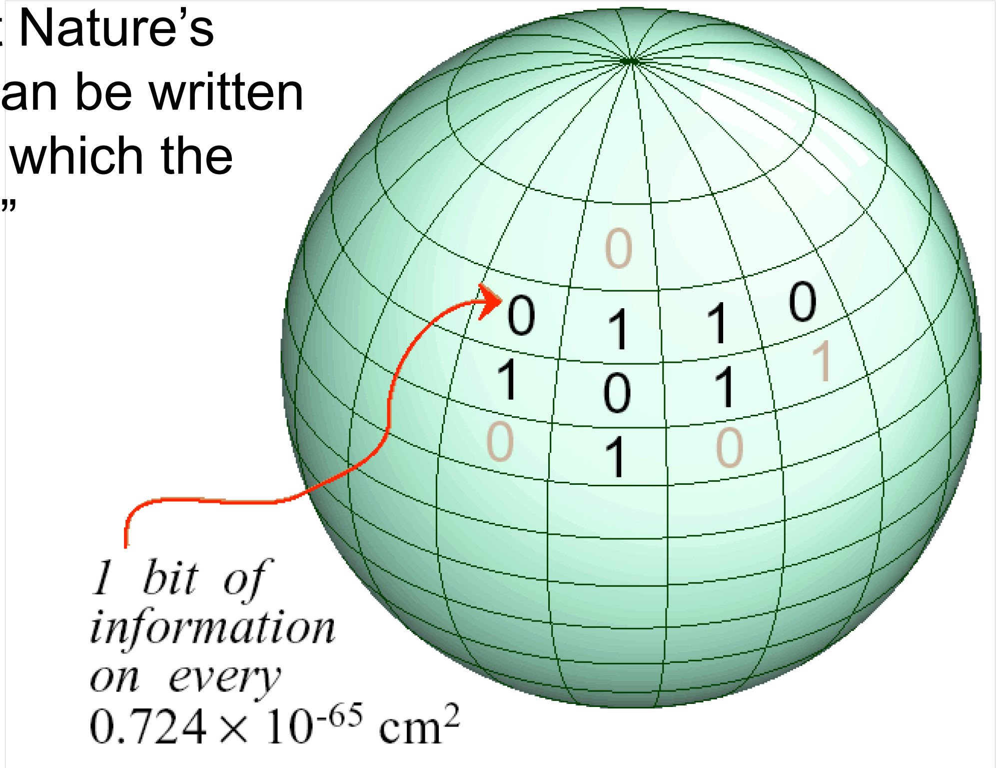
CJH: arXiv:0905.4803

Bold idea from black hole physics: the world is a hologram

"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."

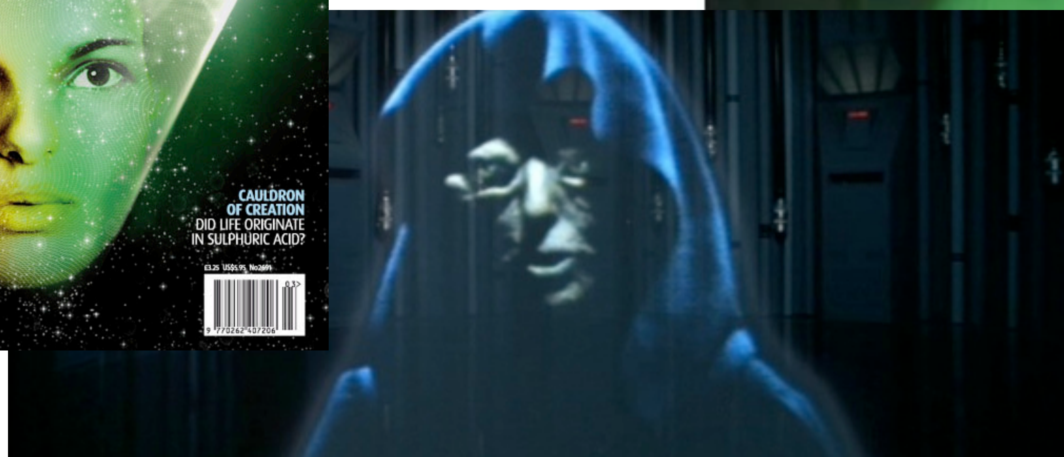
-Gerard 't Hooft

***Everything* is written on 2D surfaces moving at the speed of light**



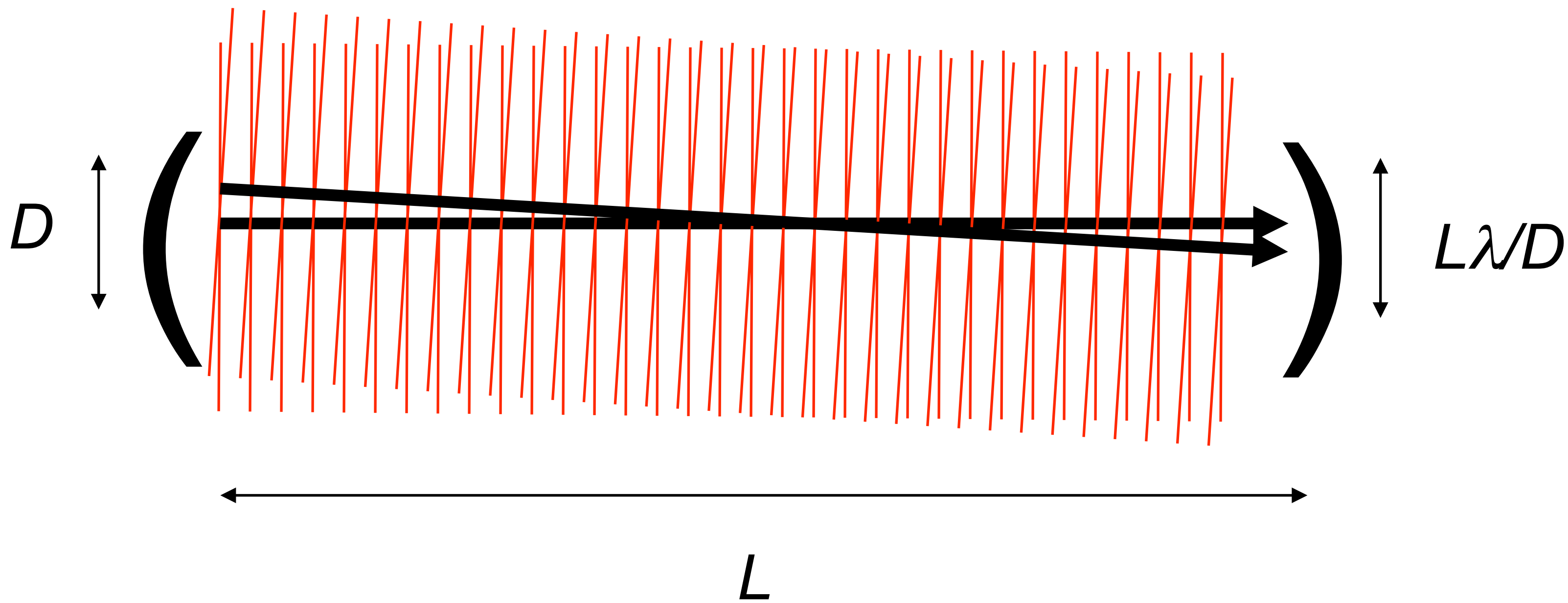
Are there experimental consequences of this idea?

A holographic world is blurred by diffraction



What does it look like "from inside"?

Rayleigh range and uncertainty of rays



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

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

Diffractive blurring in real holograms

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

- The blurring is much bigger than a wavelength of light:

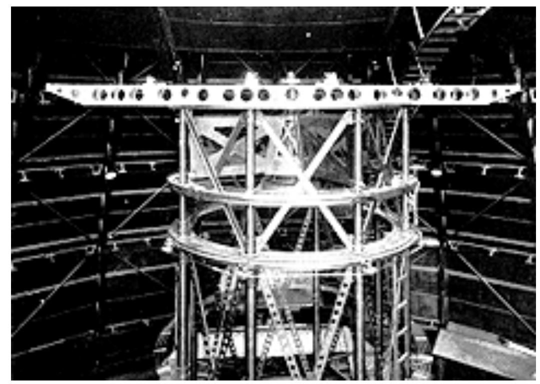
$$D = \sqrt{\lambda L}$$

is the transverse resolution at a distance *L*

- (*D* is about 1mm for an optical hologram at L= 1m)

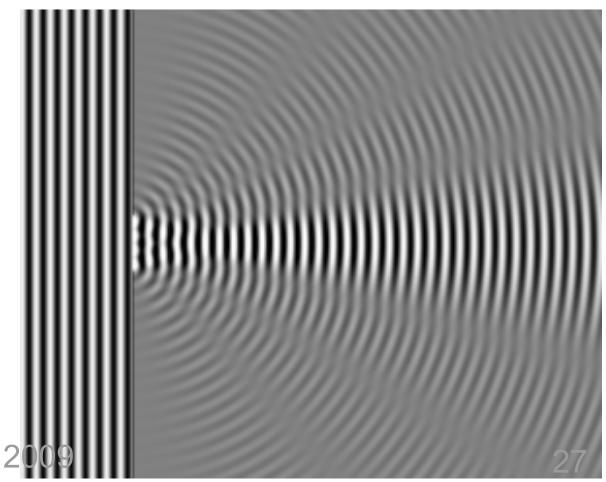
Similar examples from the world of optics

- 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

Movie made of holograms

- Make holographic frames with short laser pulses Δt
- Each frame is locally sharp, blurred on transverse scale

$$\Delta x = \sqrt{\lambda c \Delta t}$$

- Random phases: positions randomly wander from frame to frame, transversely
- wander on longitudinal separation scale ΔL over a transverse distance bounded by

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

- If reality is a movie of Planck holograms, we should observe this kind of jitter
- Sequence of frames= time in 2+1D, spacetime in 3+1D

Holographic geometry: interpretation of unified theory

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 theory

- Black holes: entropy=area/4 $S = A/l_P^2 4 \ln 2$
- Black hole evaporation
- Einstein's equations from heat flow
- 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

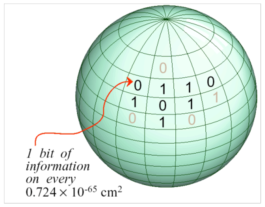
Beckenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Padmanabhan, Banks, Fischler, Shenker, Unruh

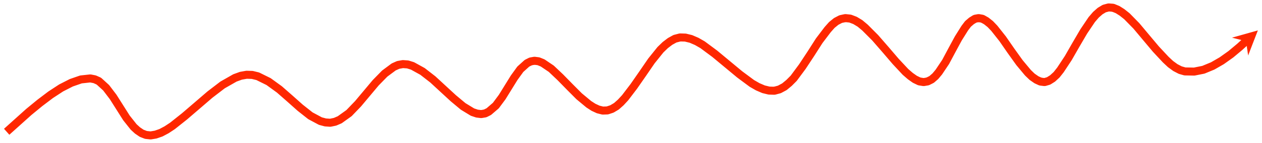
Black Hole Thermodynamics

- Beckenstein, Bardeen et al. (~1972): laws of black hole thermodynamics
- Area of (null) event horizon, like entropy, always increases
- Entropy is identified with 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?

Black Hole Evaporation: a clue to unification

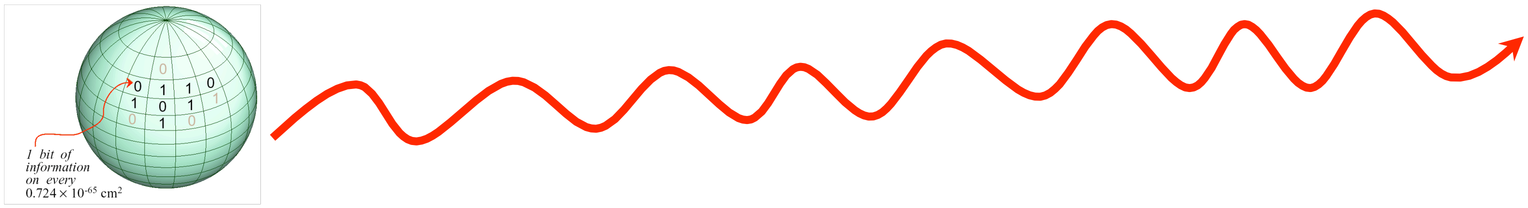
- Hawking (1975): black holes slowly radiate particles, lose energy
- They convert "pure spacetime" into normal particles like light
- number of particles = area of the surface in Planck units
- A great idea--- but not observable





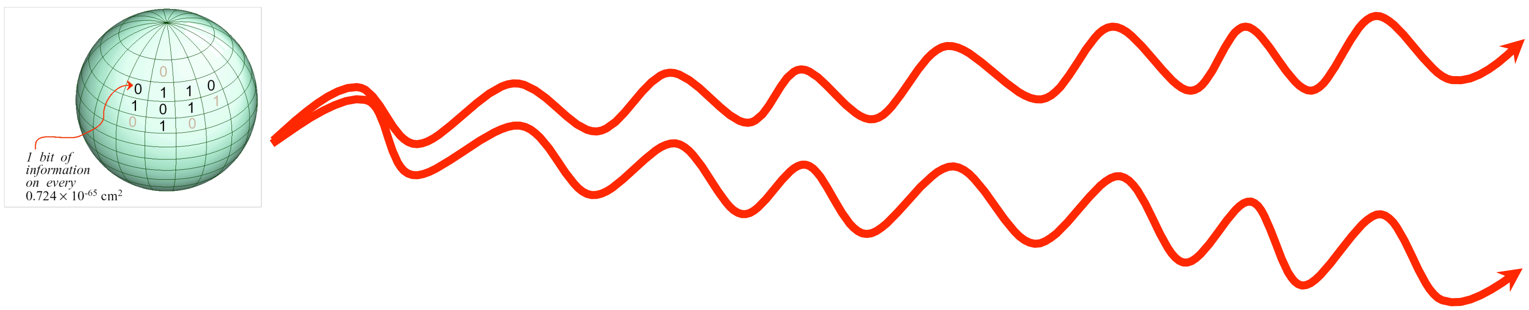
Black Hole Evaporation

- black hole radiates thermal radiation, shrinks and disappears
- 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*



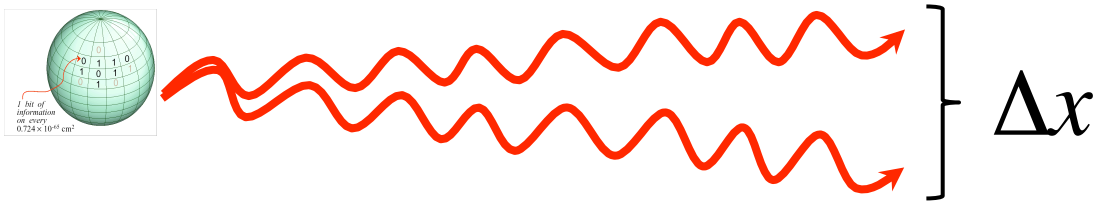
Craig Hogan, Fermilab colloquium, July 2009

New: black hole evaporation obeys quantum mechanics if distant, nearly flat space has new 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

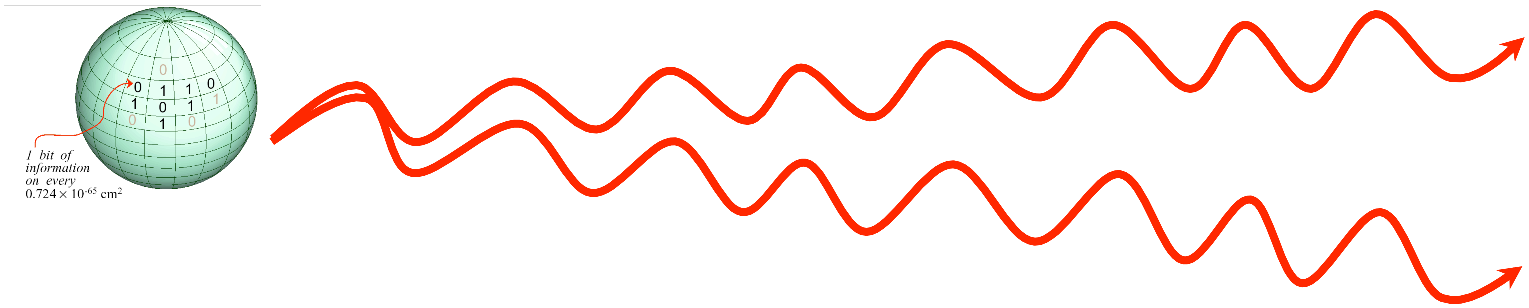
$$(L/\Delta x)^2 < (R/\lambda)^2$$

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

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

- Uncertainty of flat spacetime independent of black hole mass
- Applies to number of position states of interferometer mirrors

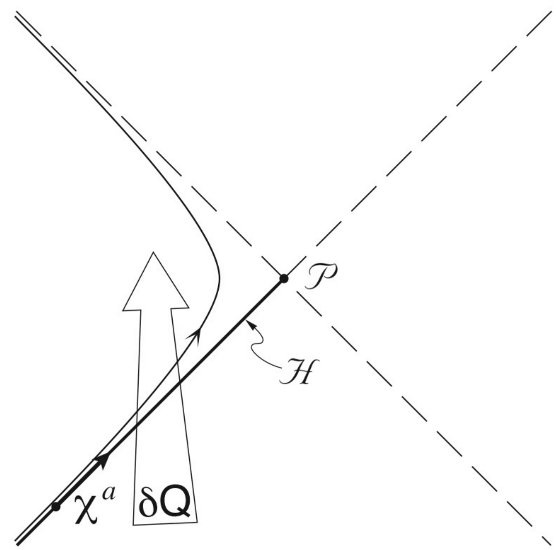
New "holographic" uncertainty of distant position….with or without a black hole



This uncertainty may be measurable!

Nearly-flat spacetime

- Unruh (1976): Hawking radiation seen by accelerating observer
- Appears with any event horizon, not just black holes



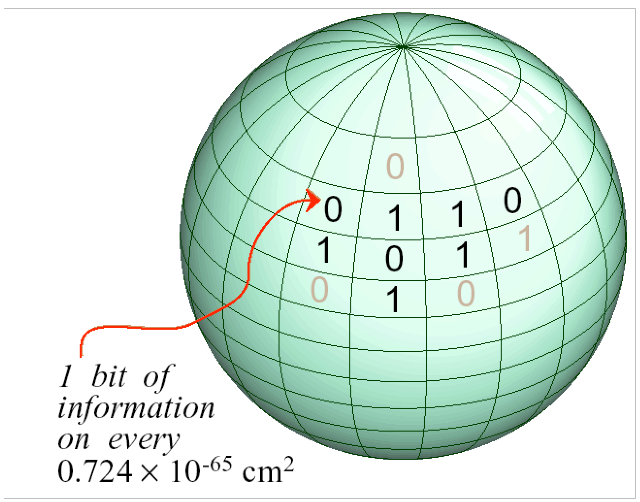
Jacobson: points=2D surfaces

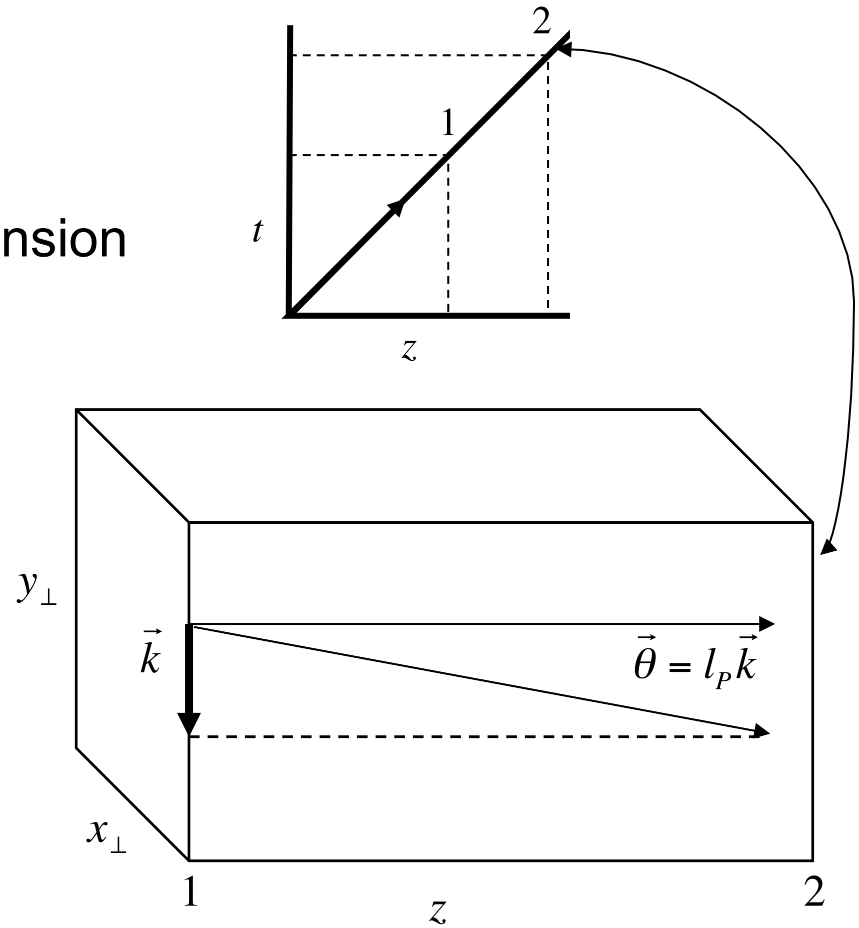
Holographic Principle

- '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 sets bound on entropy of any system; includes all quantum degrees of freedom
- All physics within a 3D volume can be encoded on a 2D bounding surface ("holographic principle")
- Bousso (2002): generalized to "covariant entropy bound”
- Suggests that 3+1D geometry emerges from a quantum theory in 2+1D: light sheets

Emergent flat 3+1D spacetime

- 3+1D from 2+1D
- Light sheets: time= *z* space dimension



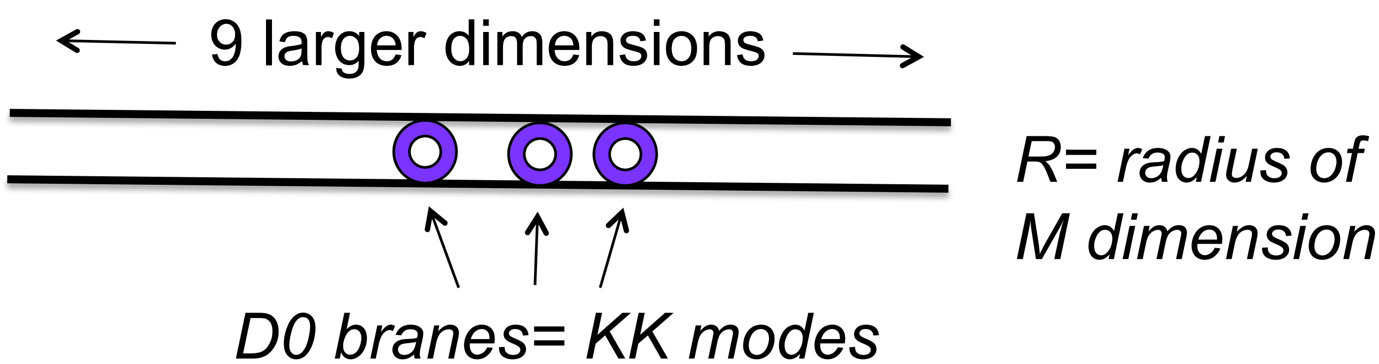


Holography and unification: String, Matrix theory

- Strominger & Vafa (1996): count degrees of freedom of extremal higher-dimension black holes using duality
- All degrees of freedom 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?
- Maldacena, Witten et al. (1997…): AdS/CFT correspondence
  - N dimensional conformal field "boundary" theory dual to N+1 dimensional "bulk" theory with gravity and supersymmetric field theory; highly curved space
- Matrix theory: wavefunctions of transverse position Matrix Hamiltonian (CJH& M. Jackson)

Example of holographic unification: 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



Macroscopic interpretation of Matrix theory

- Hamiltonian from Banks, Fischler, Shenker, & Susskind:

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

- Notions of position, distance emerge on scales >>*R*
- Two matrices encode macroscopic transverse spatial dimensions
- local in 2+1 D, “incompressible” on Planck scale: holographic
- Third dimension emerges holographically = time
- Center of mass position of macroscopic mass-energy, *x*= tr *X*
- Conjecture: third, macroscopic longitudinal position encoded by first (kinetic) term, conjugate momenta to position matrices

Macroscopic wave equation from Matrix theory

- Matrix Hamiltonian stripped to macroscopic essentials

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

- Substitute wave operators for matrix operators

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

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

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

Macroscopic wave equation from Matrix 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
- effective wave equation: "Bohr atom" for spacetime

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

Solutions of wave equation mix dimensions

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

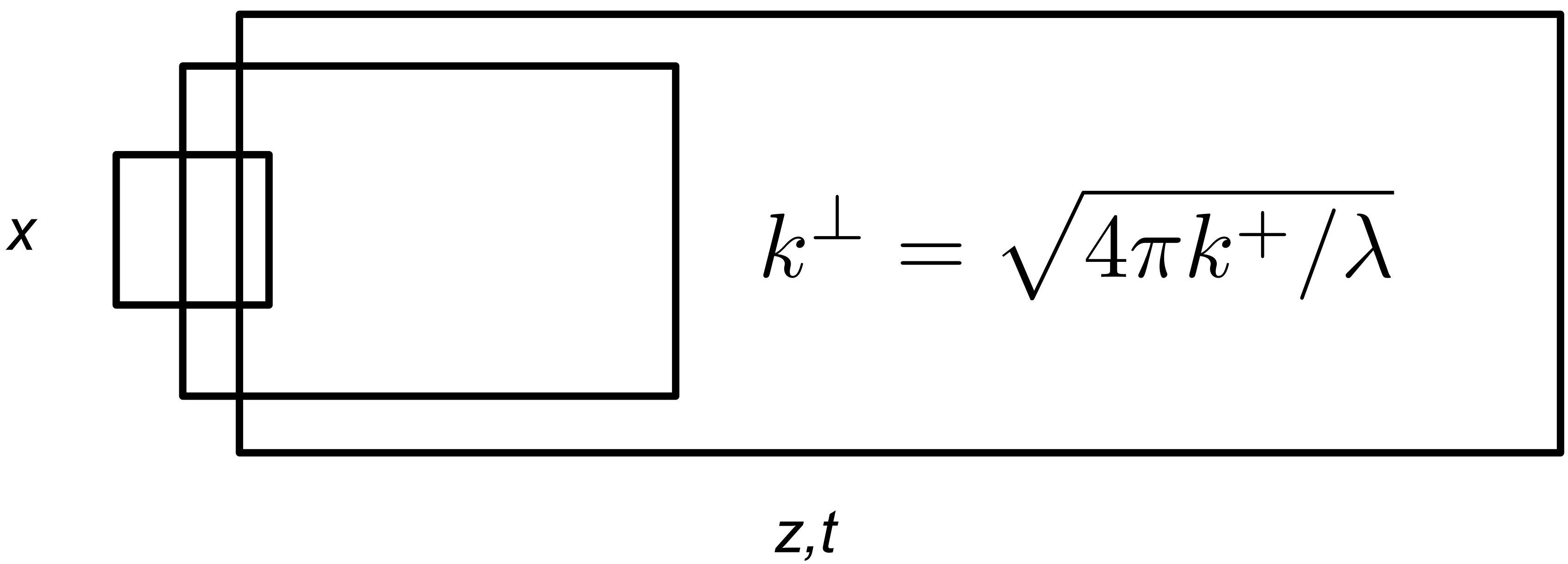
Solutions display diffusion, diffraction:

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

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

Nonlocal modes mix longitudinal and transverse positions

- Wave solutions: “Holographic geometry”
- New macroscopic behavior, not the same as field theory limit



New uncertainty principle: transverse widths of wavepackets

Standard transverse position and momentum uncertainty

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

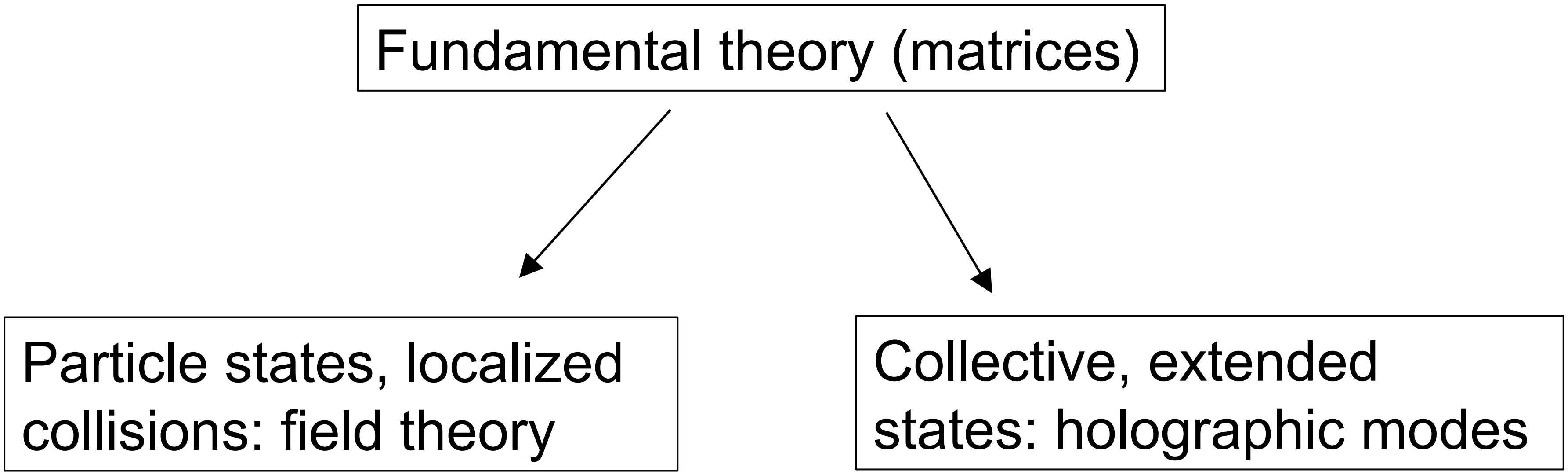
Longitudinal extent of system from dispersion relation

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

Uncertainty in transverse position on scale *L*

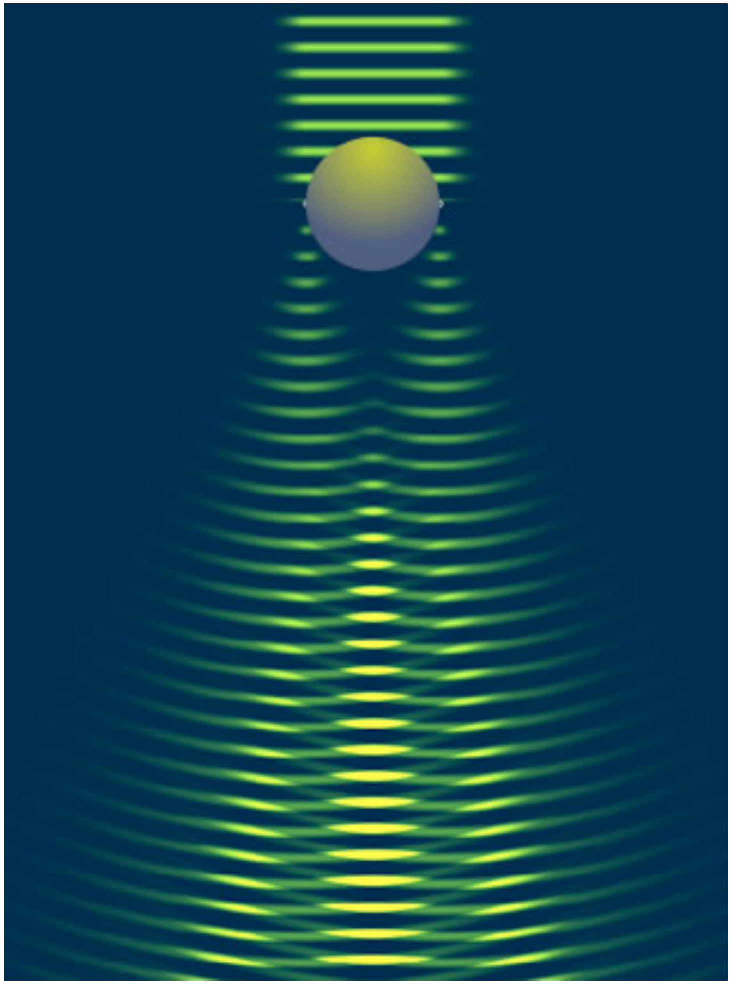
$$\langle \Delta x^2 \rangle > \lambda \Delta L^+/2$$

Different limits of Matrix theory



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



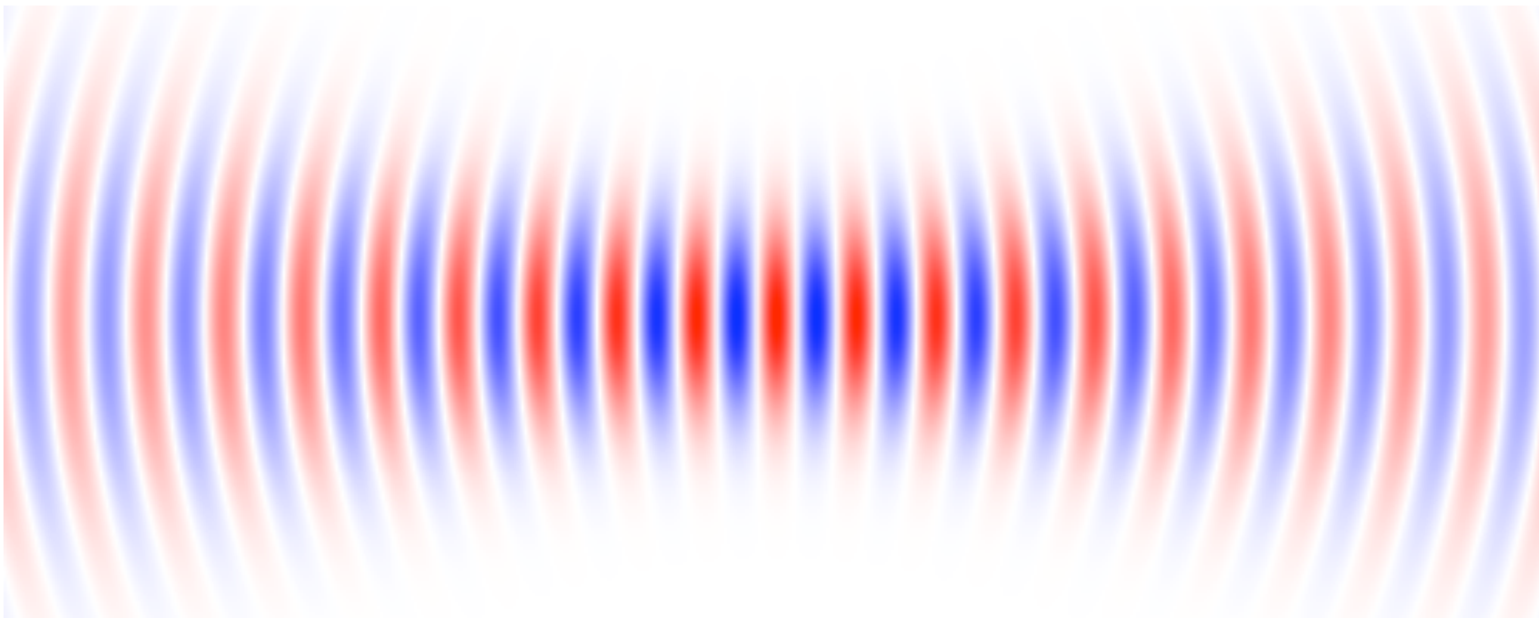
Paraxial wave equation

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

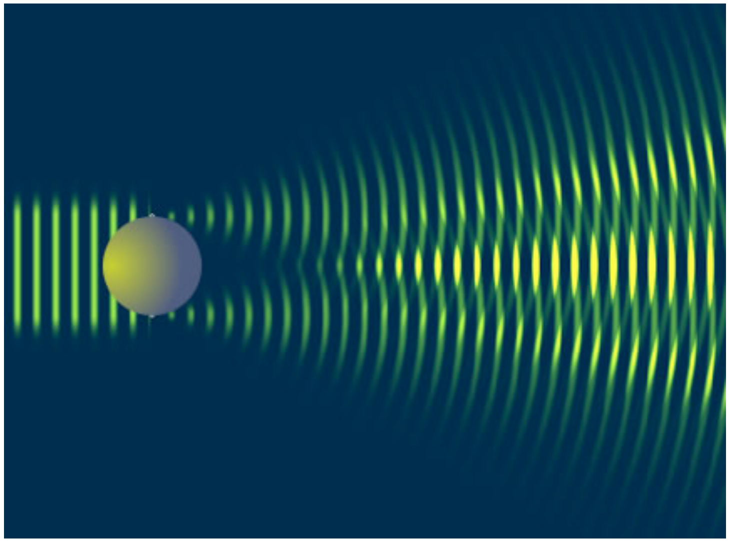
$$\frac{\partial^2 u}{\partial x^2} - \frac{4\pi i}{\lambda}\frac{\partial u}{\partial z} = 0$$

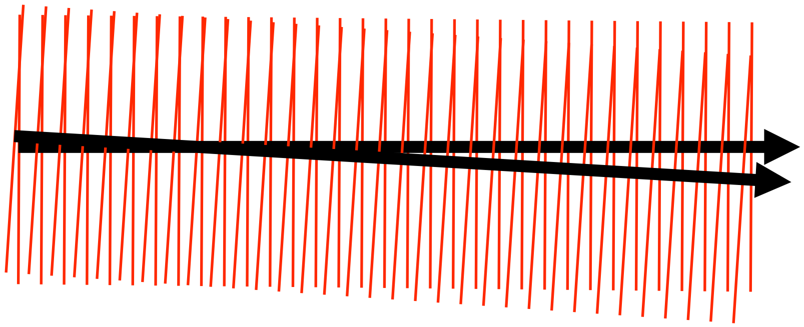
- Basis of laser wave optics
- Same as wave equation from Matrix theory
- Solutions display diffraction: e.g. laser cavities
- reinterpret as a position wavefunction of mass-energy

Gaussian Beam solutions of paraxial wave equation



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

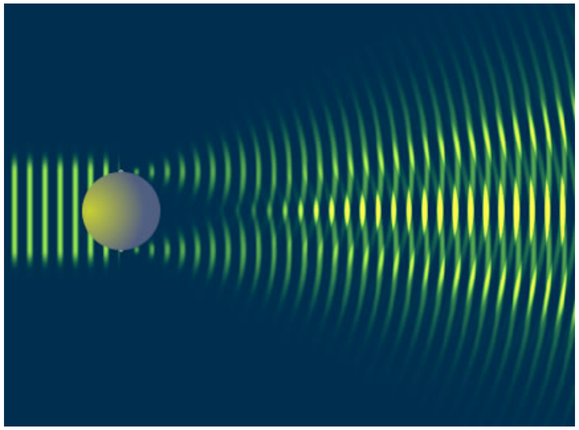
holographic approach to the classical limit

- 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:

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



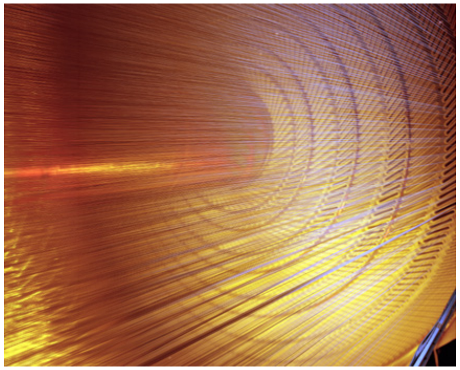
- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

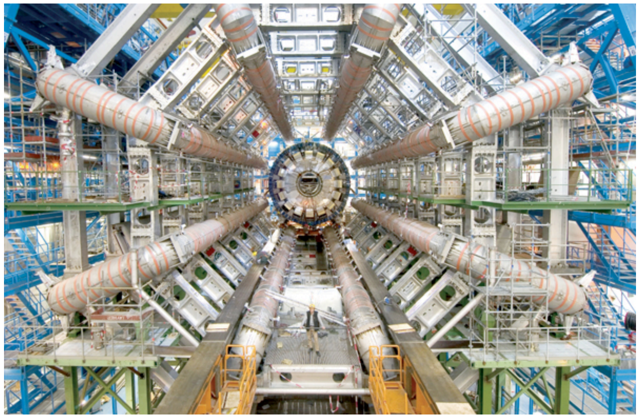
Holographic Noise in Interferometers

- Nonlocality: uncertainty in relative transverse positions at macroscopic separation
- Effective jitter in position relative to classical geodesics
- Random variation in arm length difference appears in signal

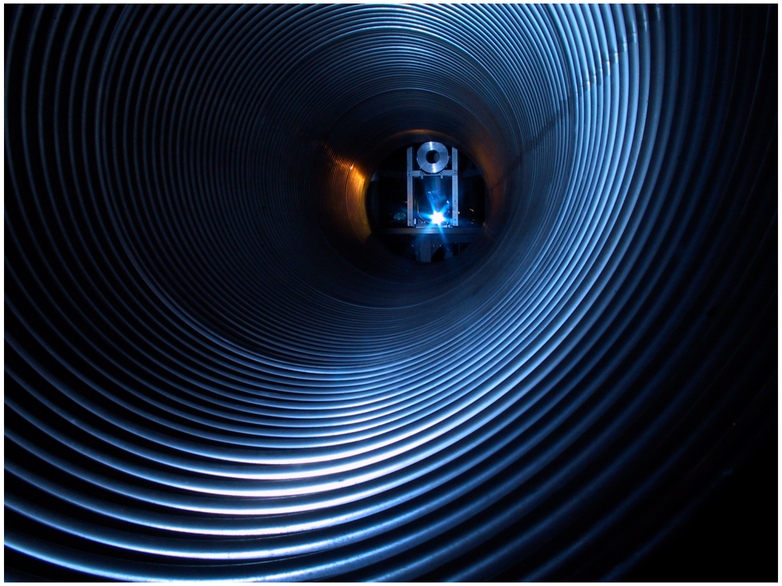
Measurement of holographic uncertainty requires coherent transverse position measurement over macroscopic distance

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



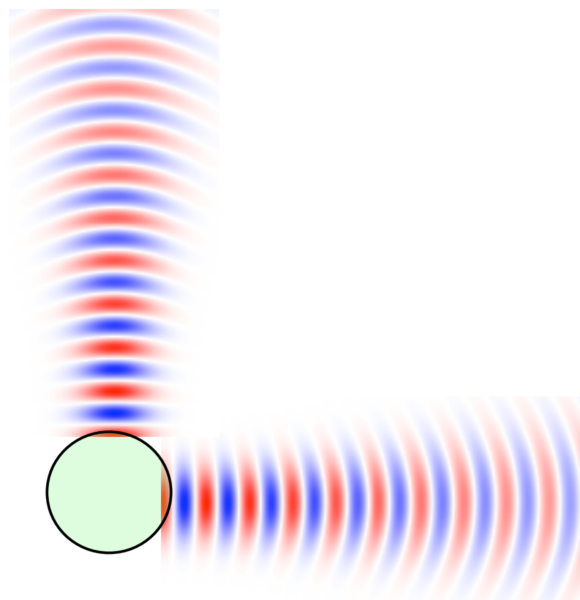


LIGO/GEO600: $\sim 10^{-18}$ m, over $\sim 10^{3}$ m



Interferometer with Planck radiation

No “better measurement” of position is possible



Quantum limit of a Planck wave interferometer

Uncertainty of mirror position and photon momentum

$$\Delta x_1 > h / \Delta p$$

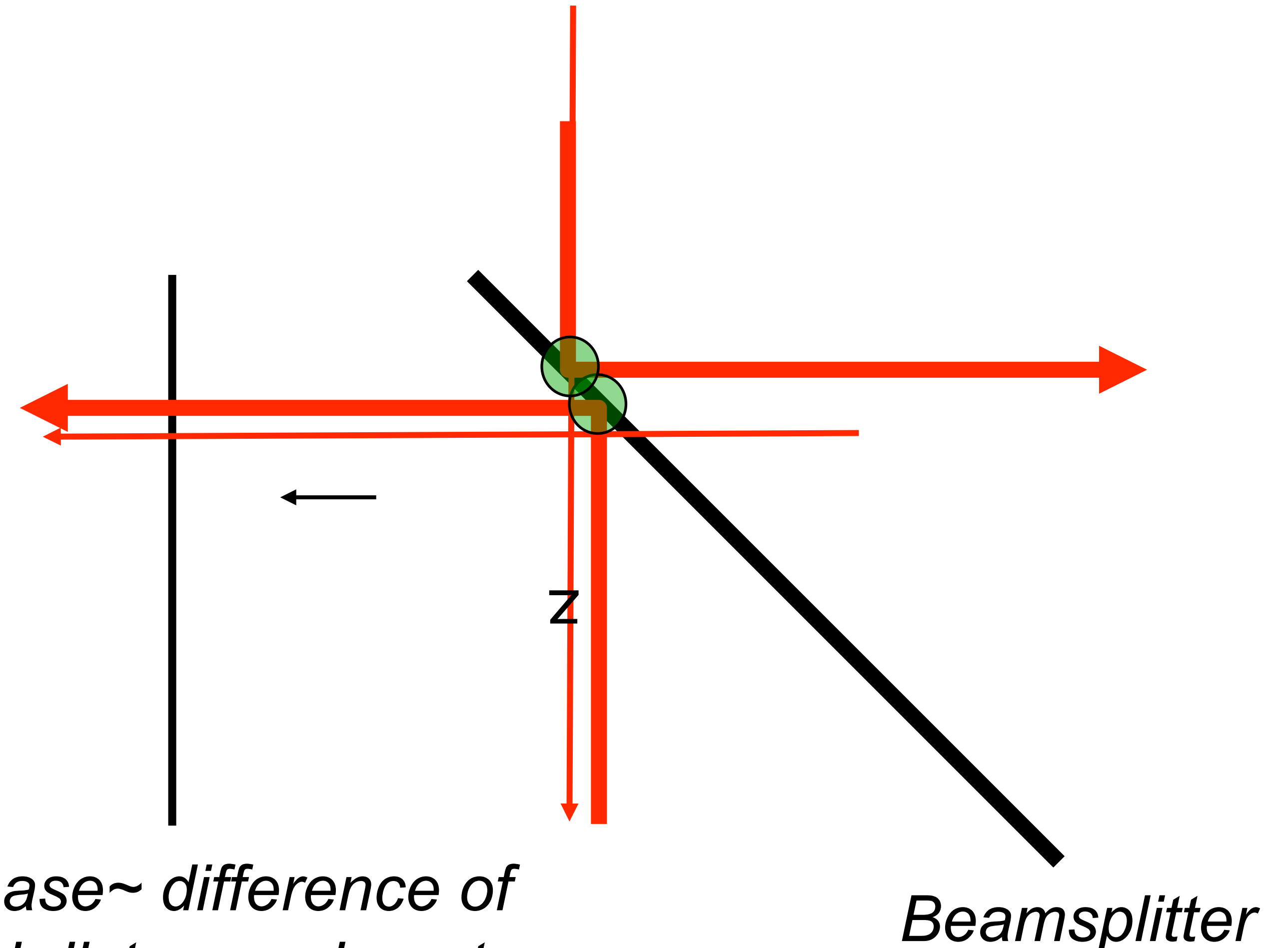
Uncertainty of position from measured phase

$$\Delta x_2 > L(\Delta p / p)$$

Minimum total uncertainty

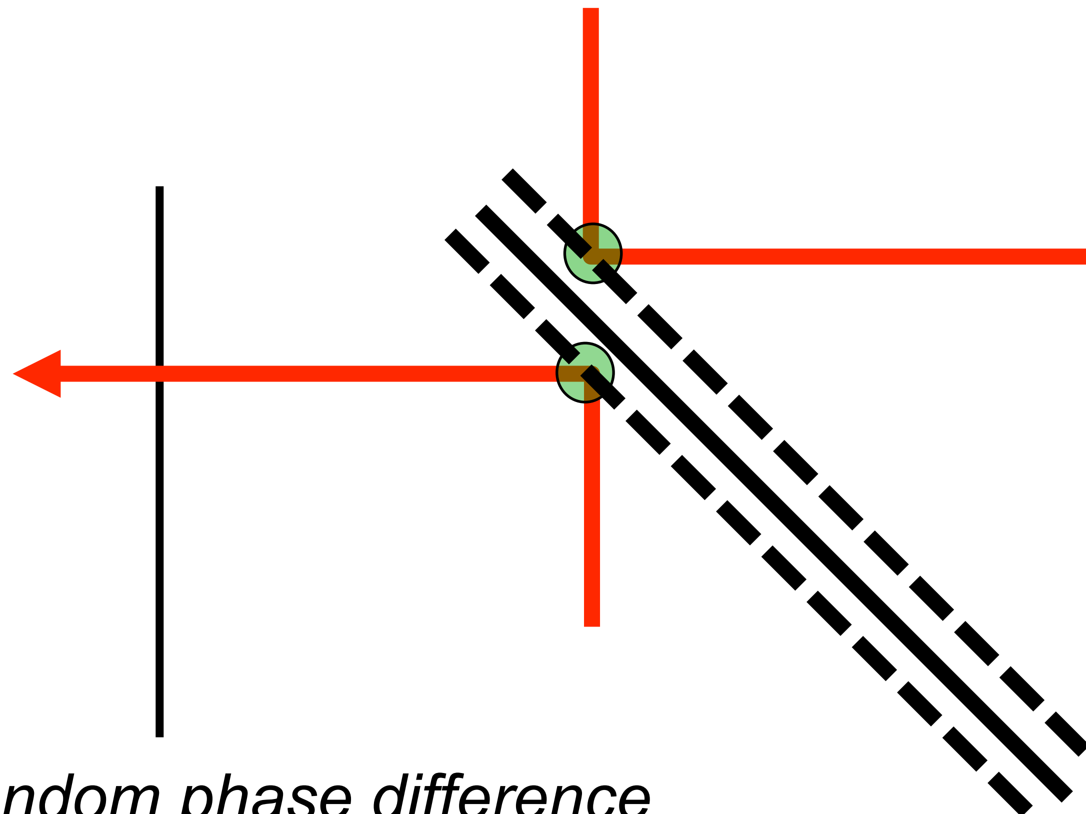
$$\Delta x_{total} > \sqrt{\lambda_P L}$$

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

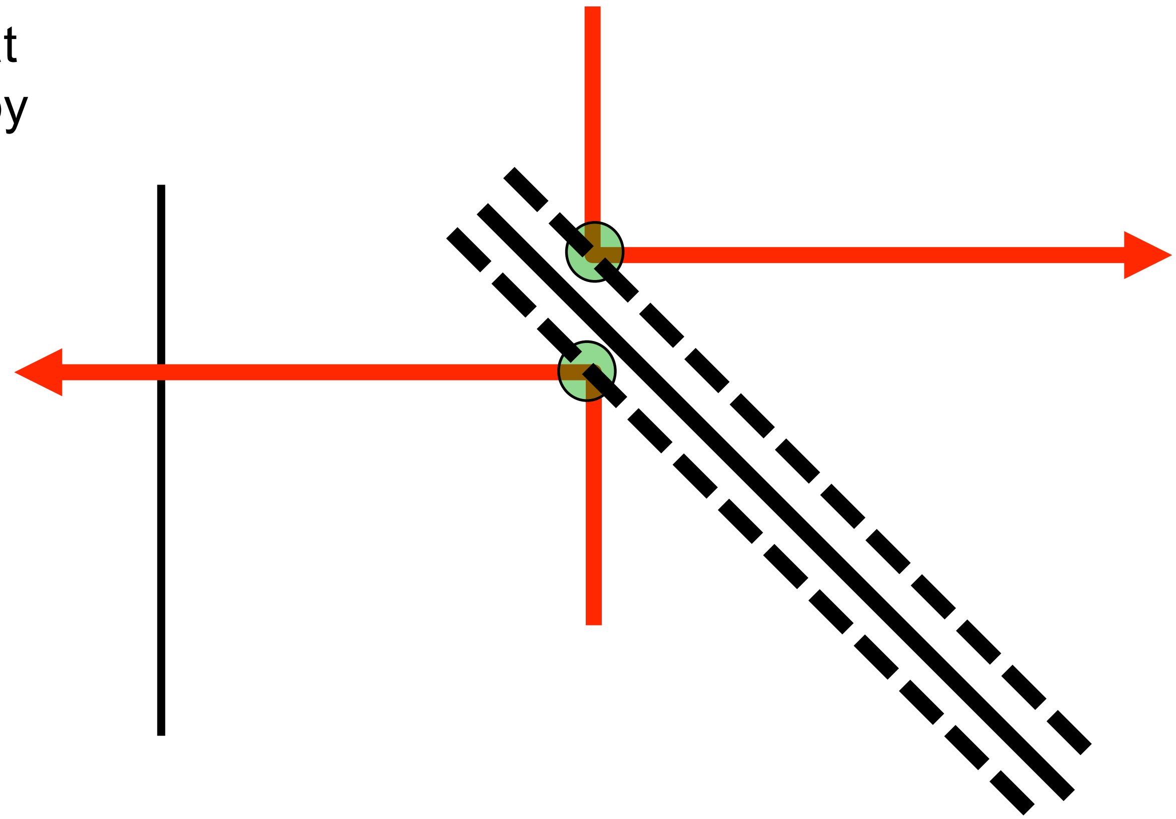


reflection events at two times separated by 2L/c

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

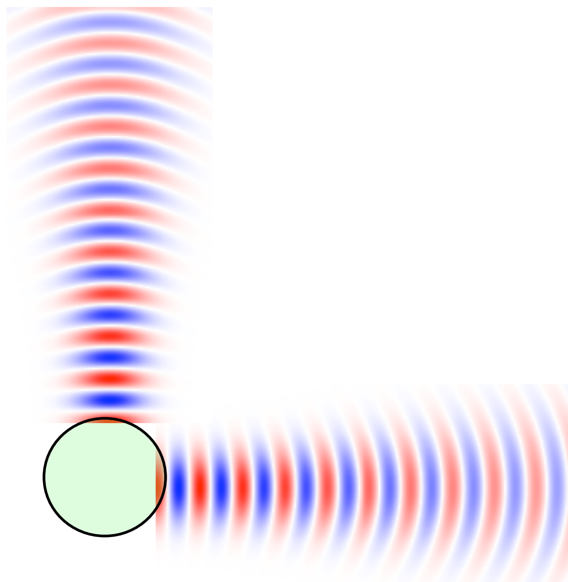


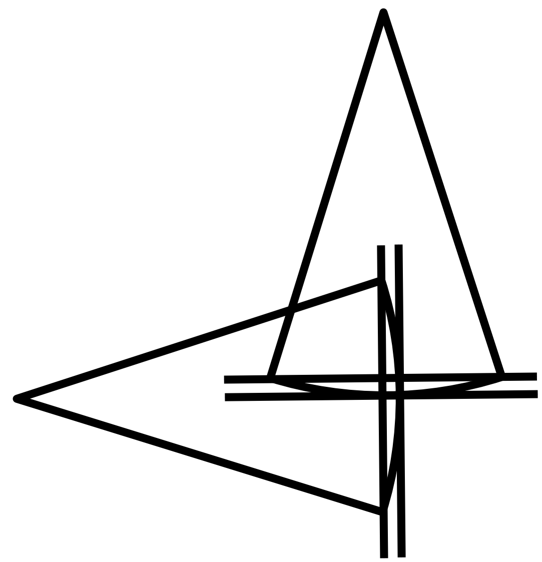
- apparent arm length difference is a random variable, with variance

$$L\lambda / \pi$$

this is a new effect predicted with no parameters

State of apparatus: squeezed in two directions





Holographic noise does not carry energy

- flat space, no metric perturbations
- No curvature, no strain
- Fluctuation in relative position of massive bodies
- “Movement without Motion”
- sampling or pixelation noise, not thermal noise
- Bandwidth limit of spacetime relationships

Power Spectral Density of 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 amplitude spectral density of ***shear*** *perturbations:*

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

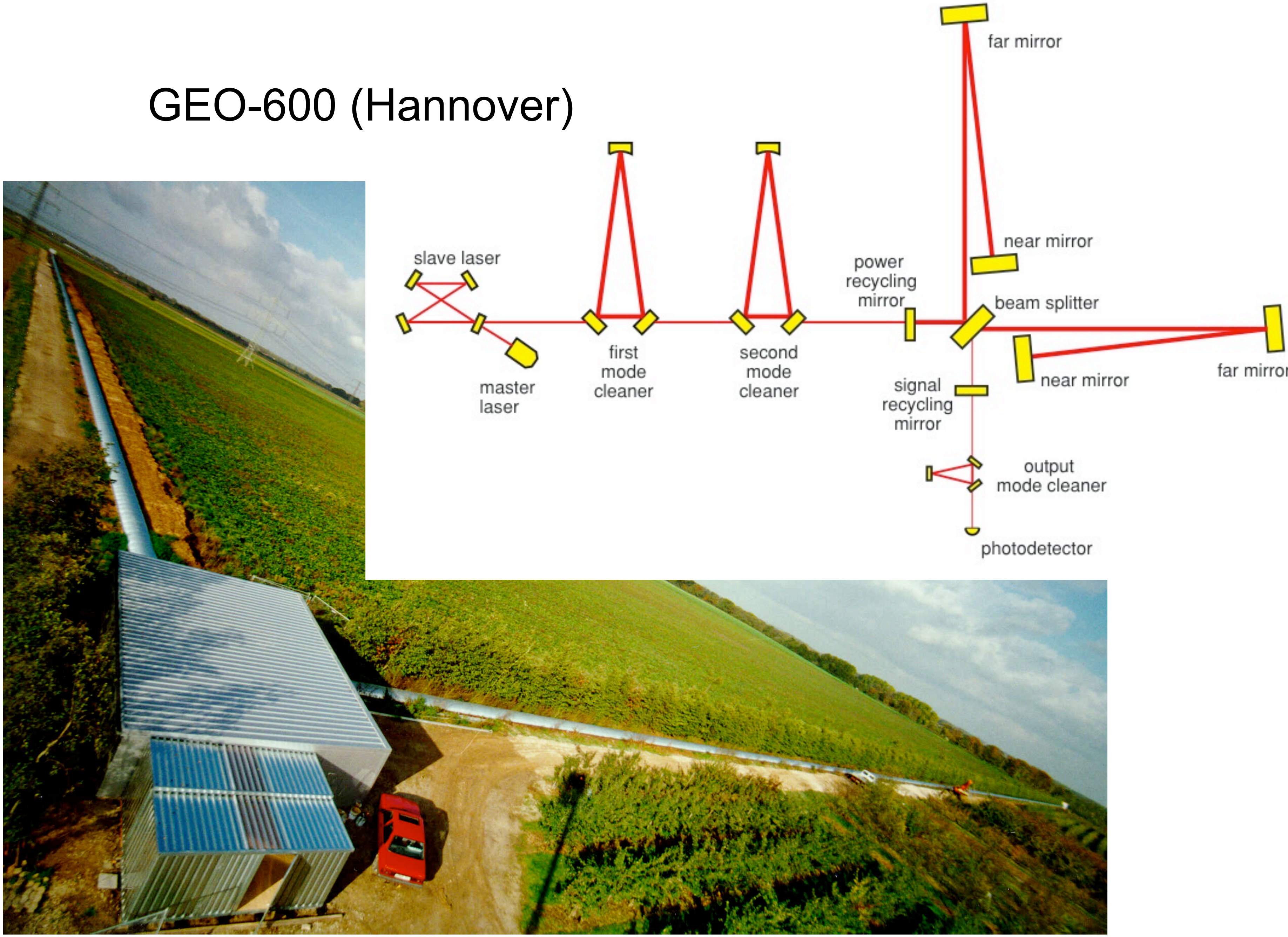
•spectrum with no parameters
•spatial shear character: different from strain
•Amplitude spectral density of equivalent strain, at low frequencies, in folded Michelson interferometer:

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

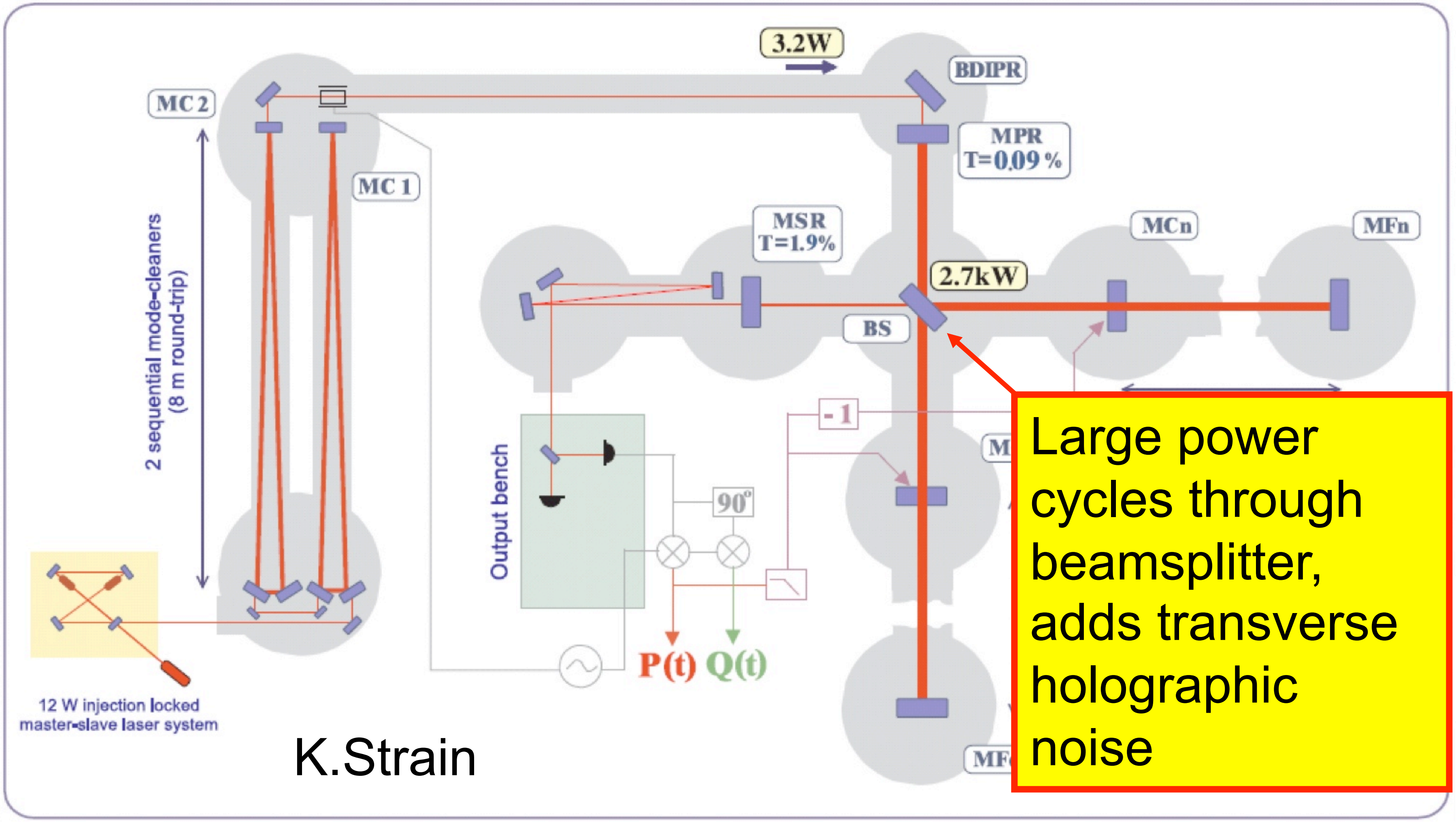
Response of interferometers

- Shear not strain: different from gravitational waves
- Folded arms do not amplify effects of shear
- GEO600 better than LIGO
- Mimics bounded random walk of beamsplitter

GEO-600 (Hannover)



The GEO600 Interferometer



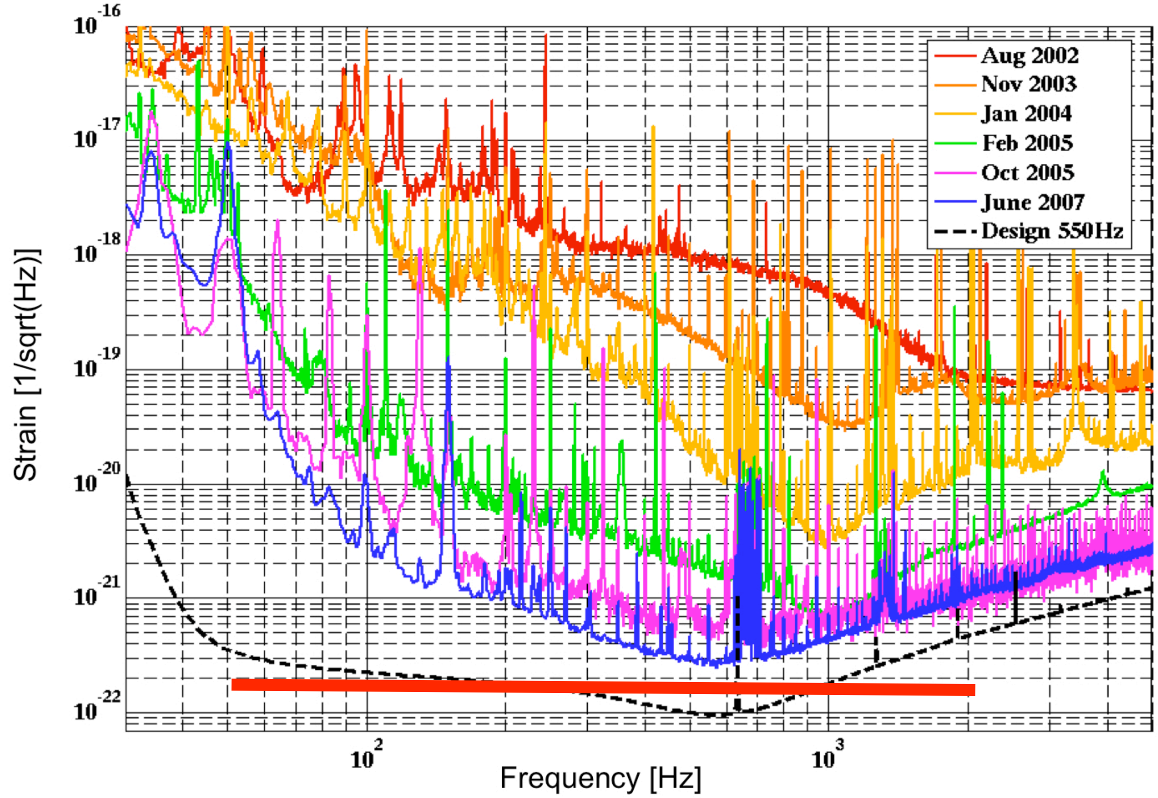
Large power cycles through beamsplitter, adds transverse holographic noise

K.Strain

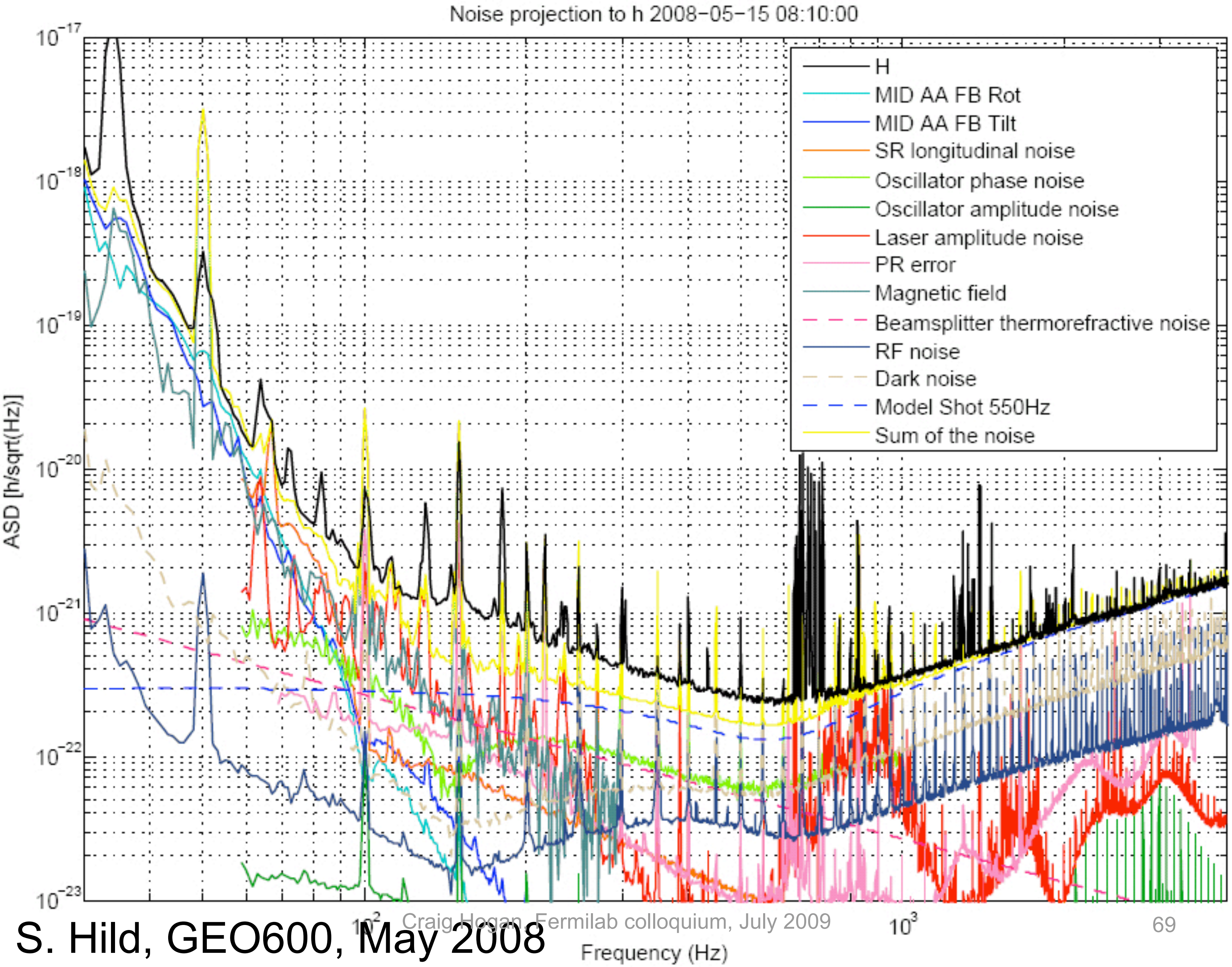
Noise in GEO600 over time

GEO Sensitivities

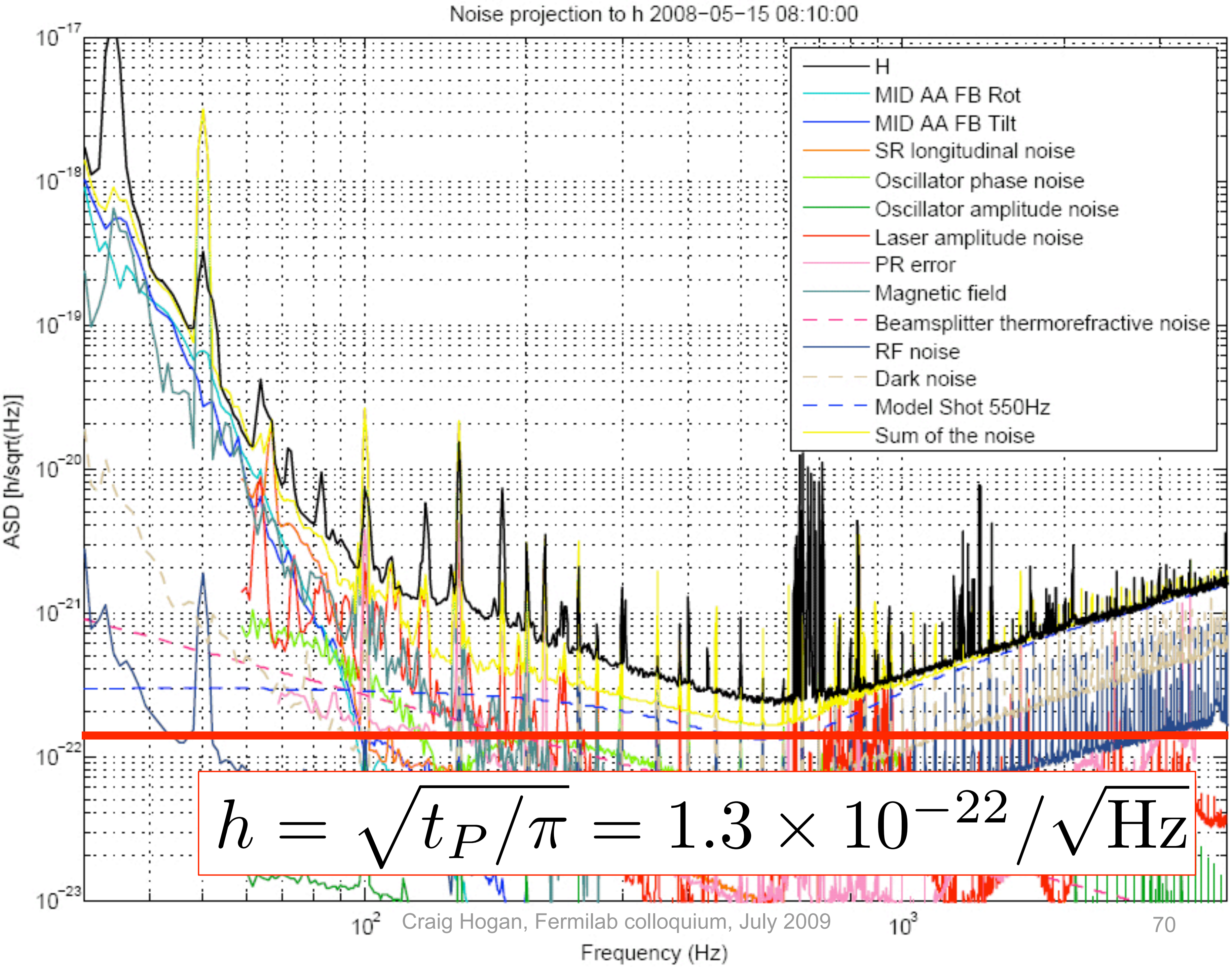
K.Strain



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

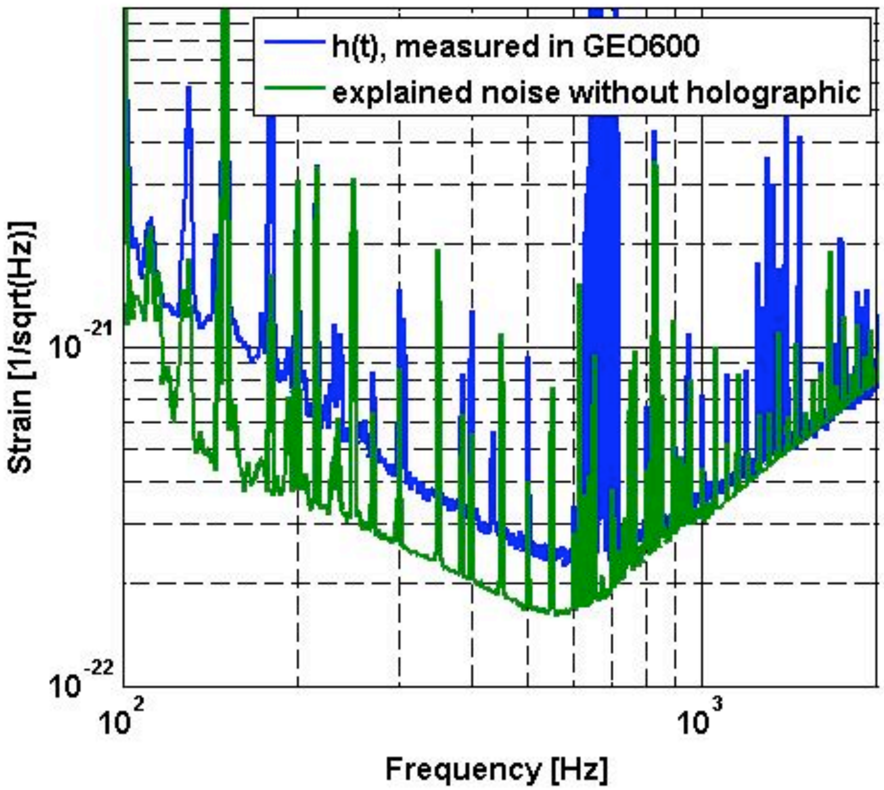


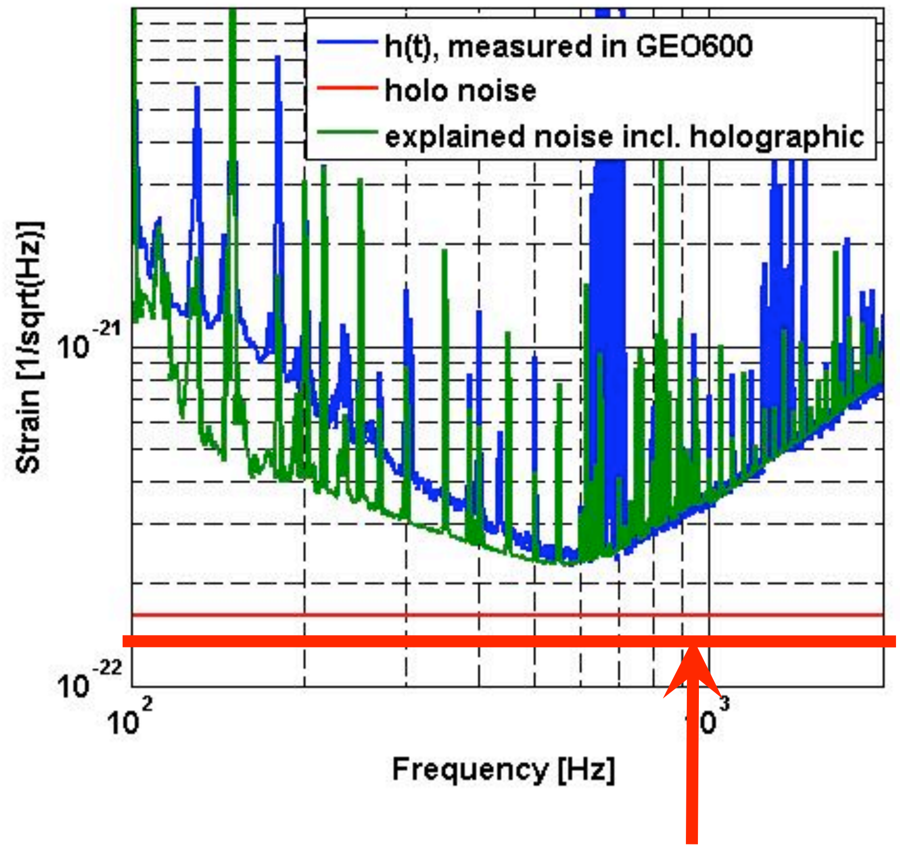
S. Hild, GEO600, May 2008



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

"Mystery Noise" in GEO600





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

Data: S. Hild (GEO600)

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

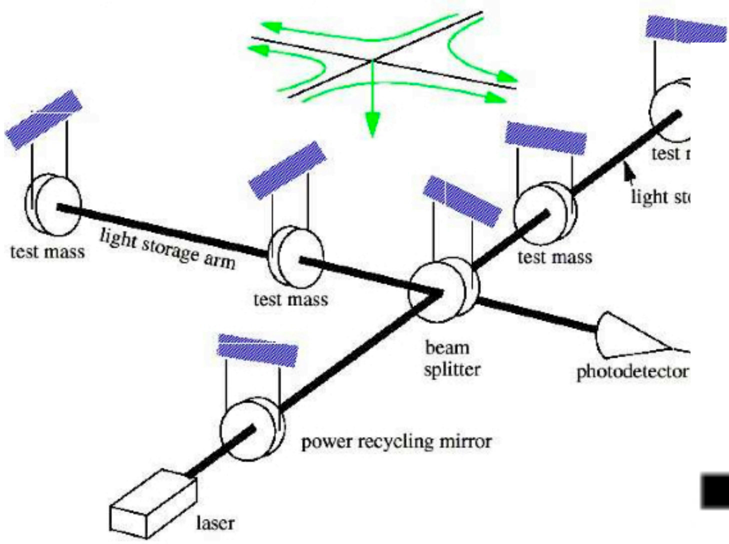
zero-parameter prediction for holographic noise in GEO600 (equivalent GW strain)

Total noise: not fitted

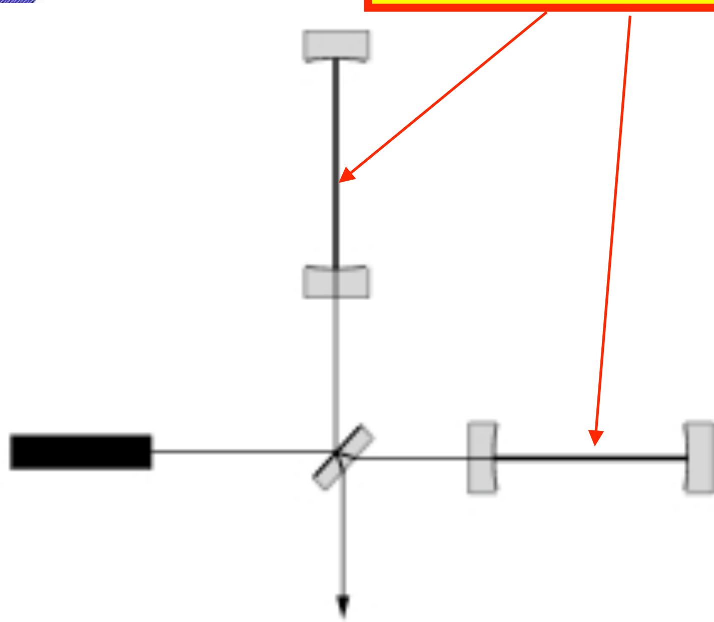
Why doesn't LIGO detect holographic noise?

- LIGO design is less sensitive than GEO600 to transverse displacement noise, but more sensitive to gravitational waves
- relationship of holographic to gravitational wave depends on details of the system layout

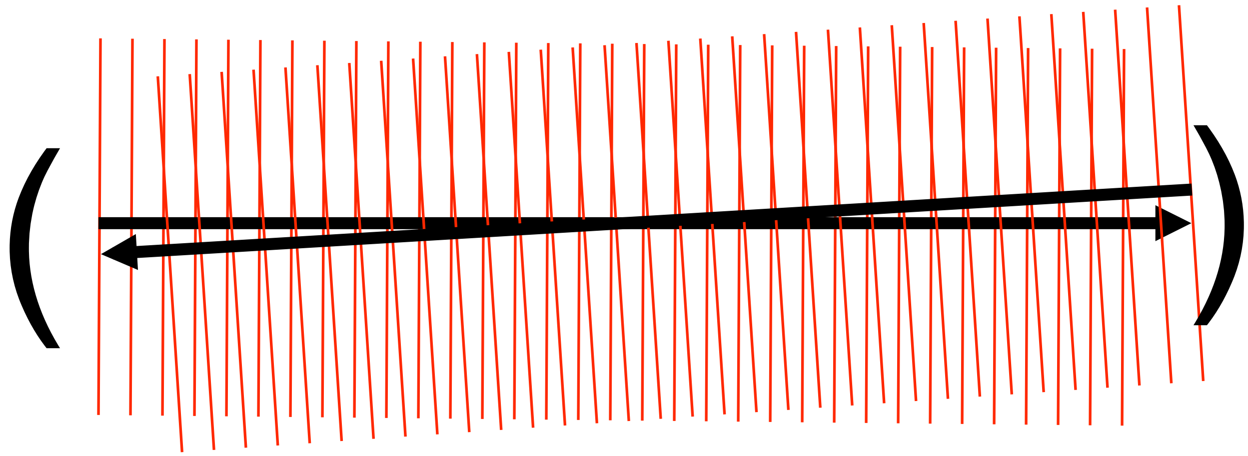
Fig. 1. Schematic layout of a LIGO interferometer.



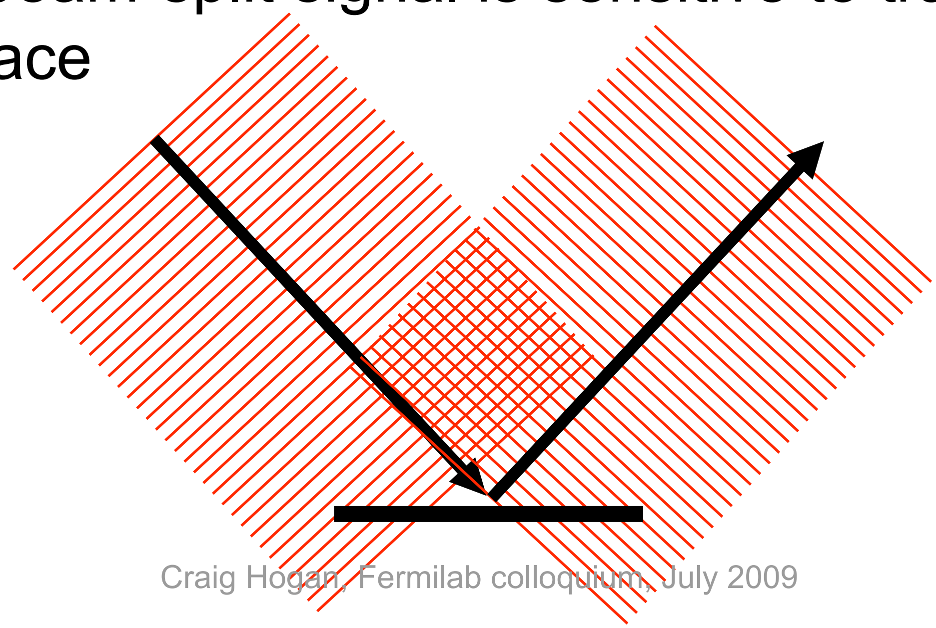
GW effect on phase is amplified in FP cavities



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

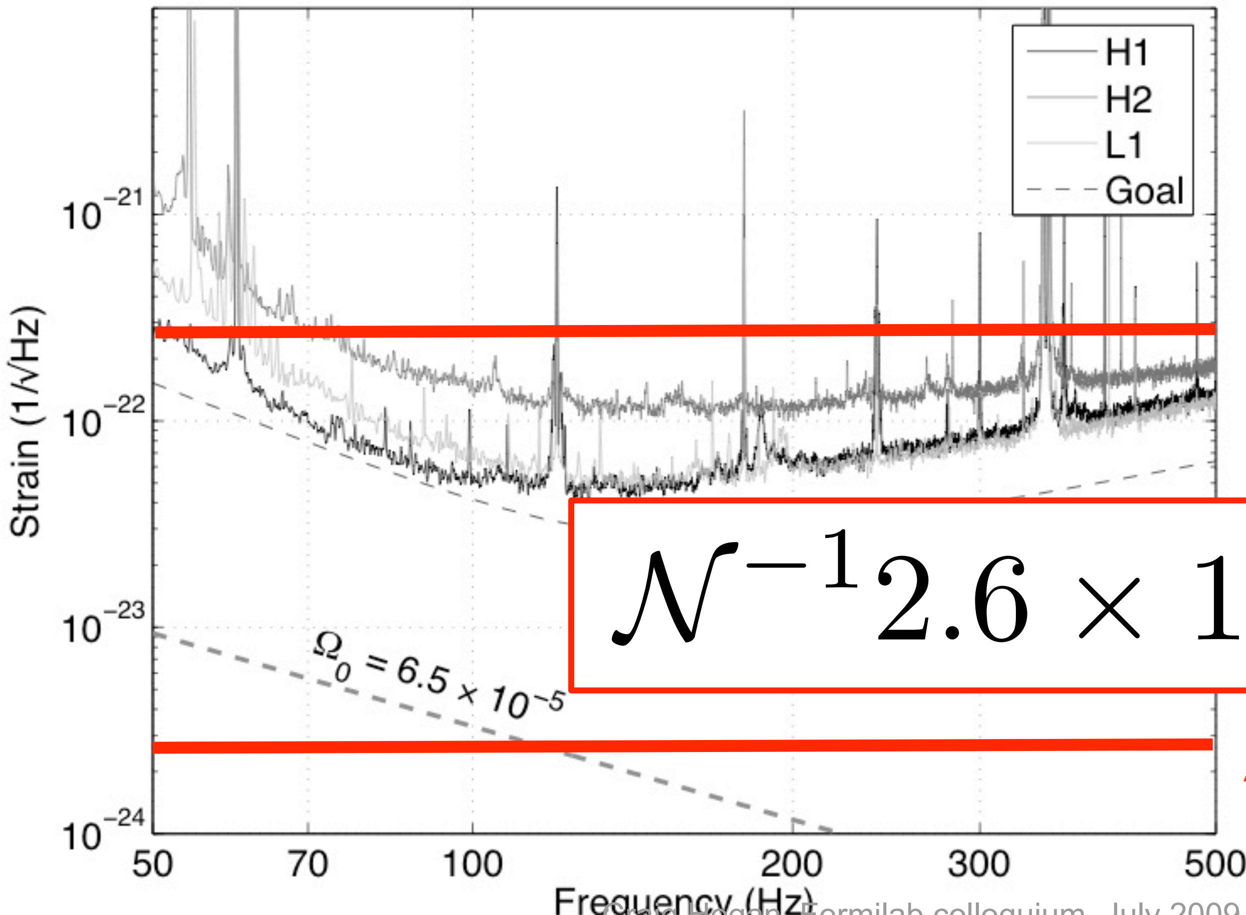


- But phase of beam-split signal is sensitive to transverse position of surface



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

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



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

About a factor of 100

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 after ~2 years of checking
- GEO600 is operating at holographic noise limit
- LIGO: current system not sensitive enough
- LIGO H1/H2 correlation: inconclusive?
- No experiment has been designed to look for holographic noise
- A definitive result is not possible with LIGO or GEO600: evidence is based on lack of other explanations
- More convincing evidence: new apparatus, based on signature coherence of adjacent systems

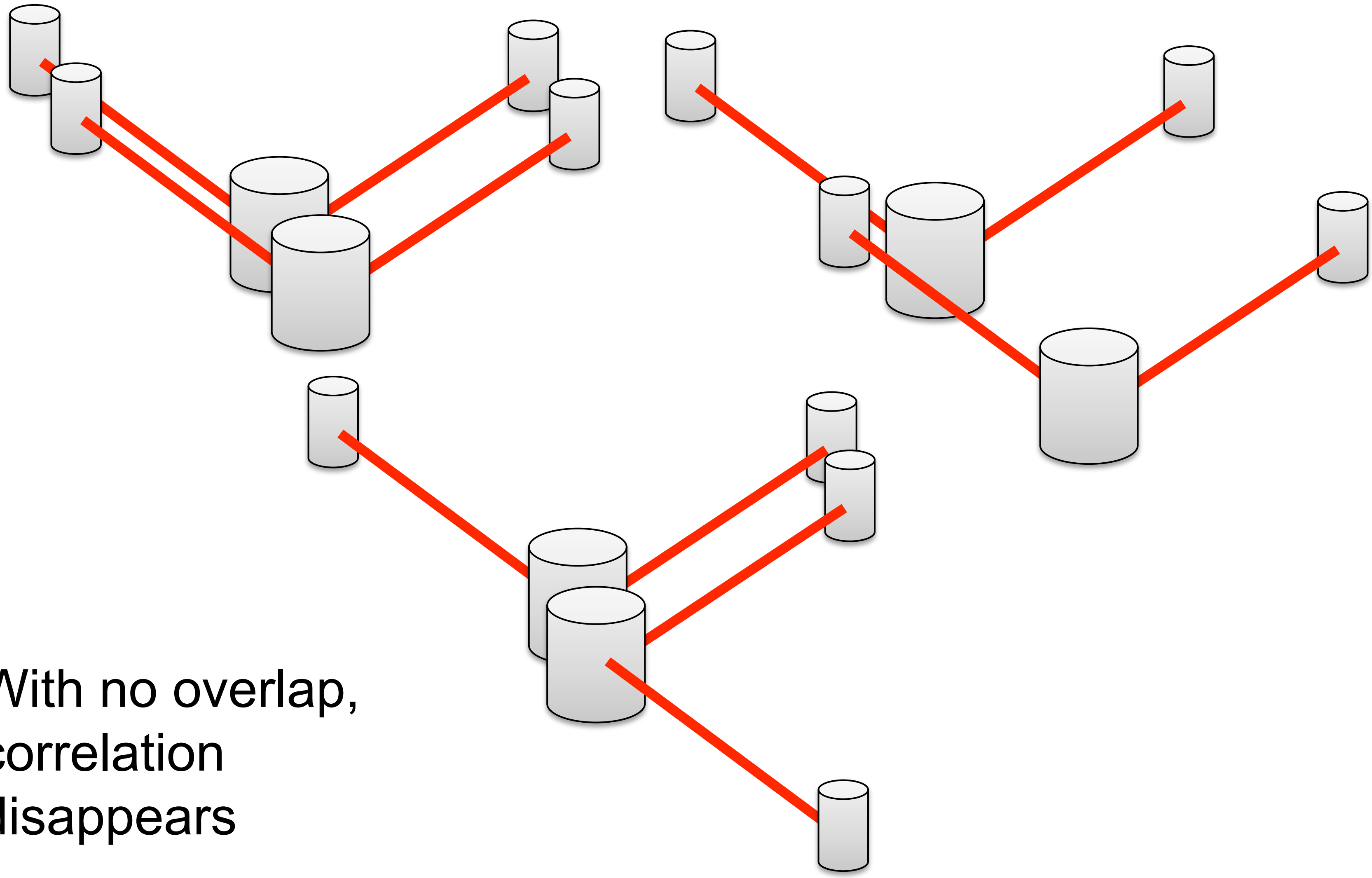
Two nearby interferometers are correlated

- Even with no physical connection, matter on a given null wavefront "moves" together
- wavefronts in adjacent interferometers, in the same direction at the same time, have almost the same transverse motion
- Proof from considering null wavefronts in the plane of interferometers with small vertical separation
- Displacements in nearby interferometers are nearly the same
- Signals are correlated in a precisely known way
- Nothing else would do this

Dedicated holographic noise experiment

- GEO600 evidence for holographic noise is based on apparatus model (i.e., lack of another explanation)
- New concept: correlation signature of holographic noise
    - predicted cross-correlation of signals in nearby interferometers
- Other noise sources are uncorrelated, average to zero
- Allows detection of subdominant holographic component
- shorter arms, higher frequency, easier suspension and optics
- Correlations modulated by reconfiguring

Correlation varies with configuration



With no overlap, correlation disappears

Main noise at high frequency: photon shot noise

- Cross correlation averages to zero with time
- Trade between cavity power, size, integration time
- Time for one sigma detection of holographic signal:

$$t_{\gamma\times} \approx \left[\frac{\lambda_{opt}^2}{L^3(2\pi)^4} \right] \left[\frac{c^3}{\lambda_P^2} \right] \left[\frac{h_P}{P_{opt}} \right]^2$$

$$\approx 375 \text{ s } (P_{opt}/1000\text{w})^{-2}(L/40\text{m})^{-3}$$

Conceptual Design by Rainer Weiss

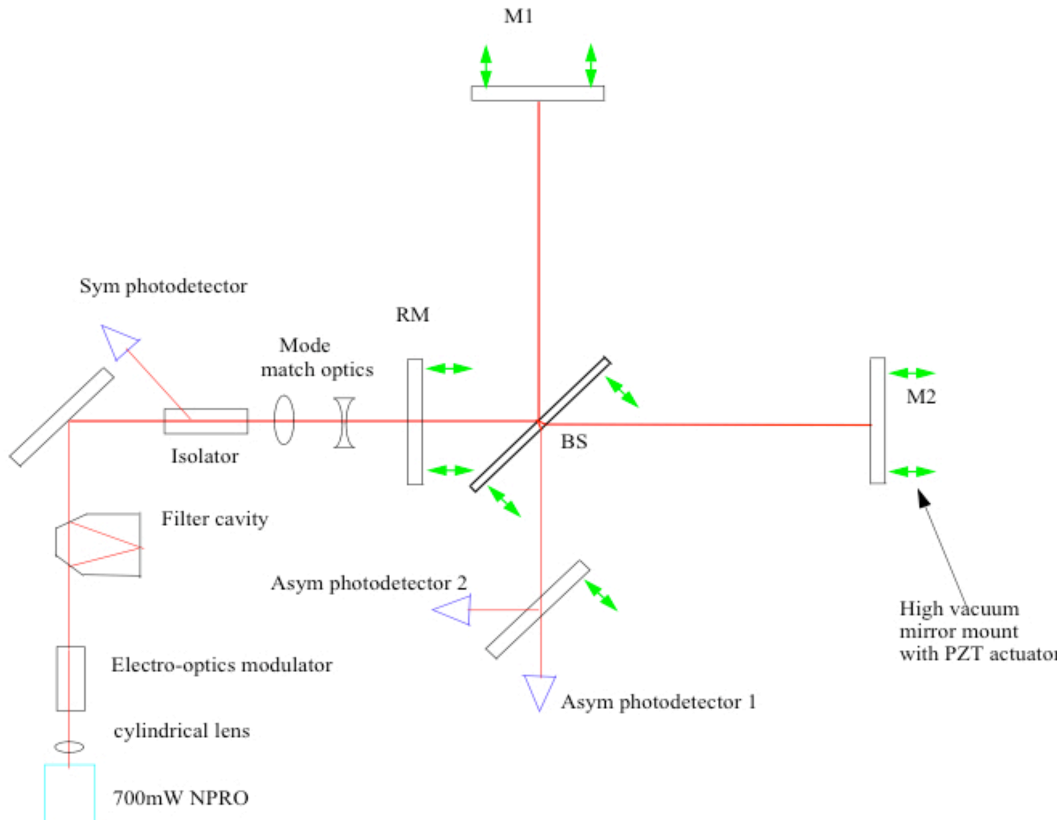
Two ~40m Michelson interferometers in coincidence

~1000 W cavity

DC sampling at ~30MHz

Simple mounts, optics

holographic noise= laser photon shot noise in ~6 minutes (1 sigma)



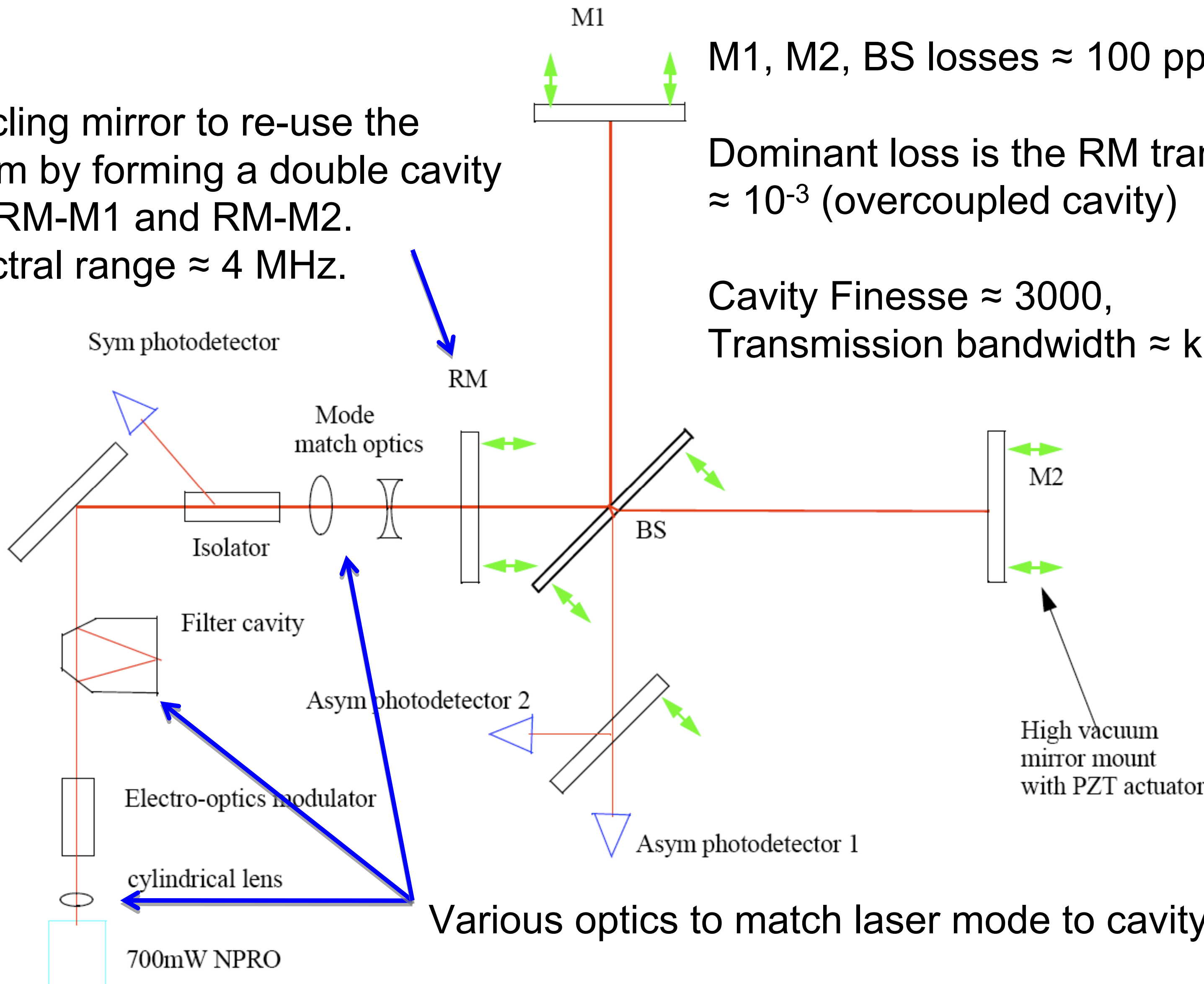
Power-recycled Michelson Interferometer

Use recycling mirror to re-use the laser beam by forming a double cavity between RM-M1 and RM-M2.
Free spectral range ≈ 4 MHz.

M1, M2, BS losses ≈ 100 ppm

Dominant loss is the RM transmission ≈ 10^{-3} (overcoupled cavity)

Cavity Finesse ≈ 3000,
Transmission bandwidth ≈ kHz

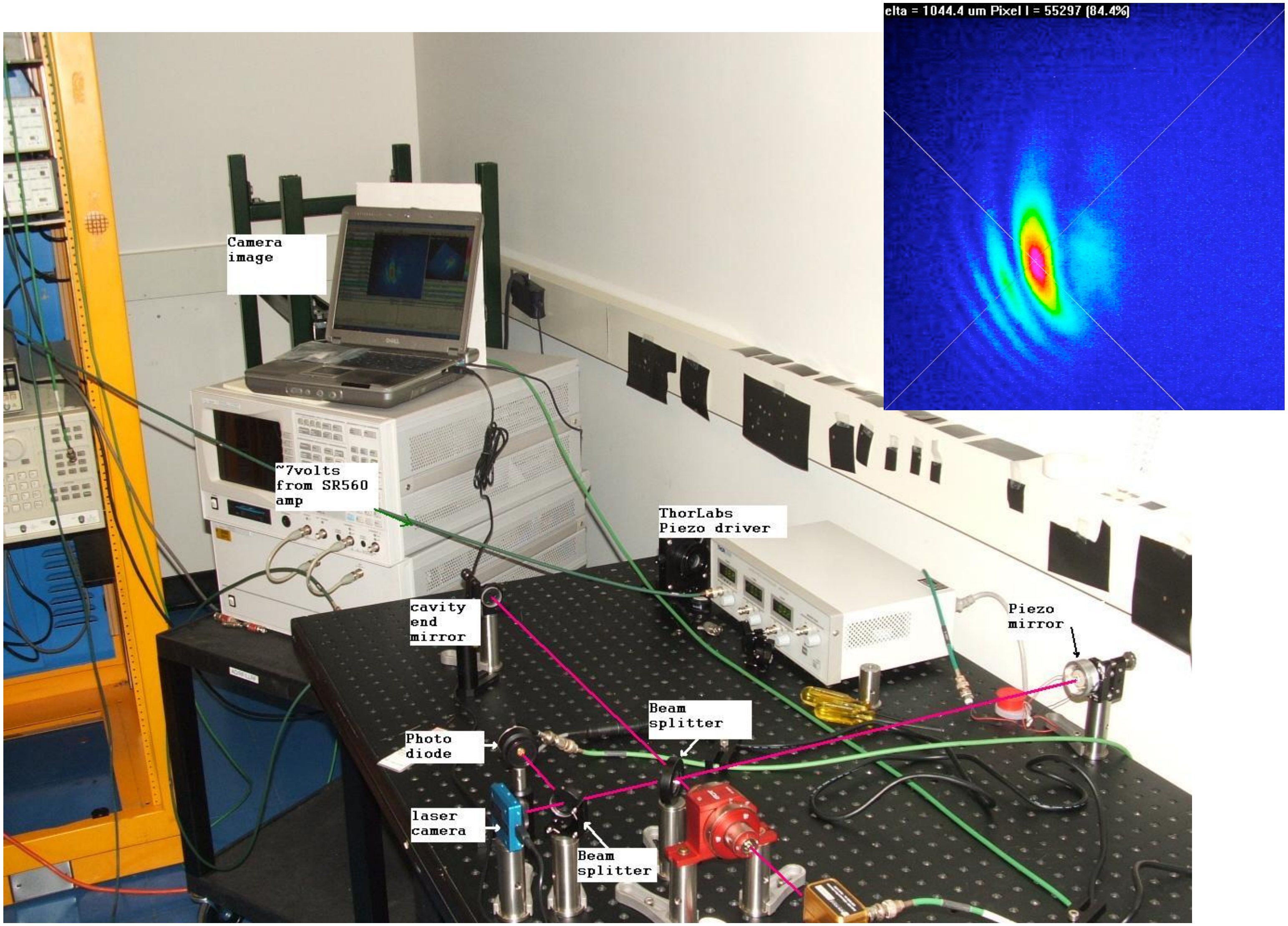


Various optics to match laser mode to cavity mode

Status of the Fermilab Holographic Interferometer

- Developing Weiss concept for correlated interferometers
- Team: Fermilab (CJH, A. Chou, W. Wester, J. Steffen, E.Ramberg, C. Stoughton, R. Tomlin, J. Ruan, C. Bhat); MIT (R.Weiss, S.Waldman), Caltech (S. Whitcomb), UC (S. Meyer), UMich (R. Gustafson), includes LIGO experts
- S. Meyer & A. Chou: UC/FNAL collaborative grant
- Building tabletop prototype in Ray Tomlin's lab
- Proposed to Fermilab PAC as new experiment, June 2009
- Estimated cost: ~ $2.3 M
- More detail at http://holometer.fnal.gov/index.html

Locked interferometer at Fermilab, 6/24/09



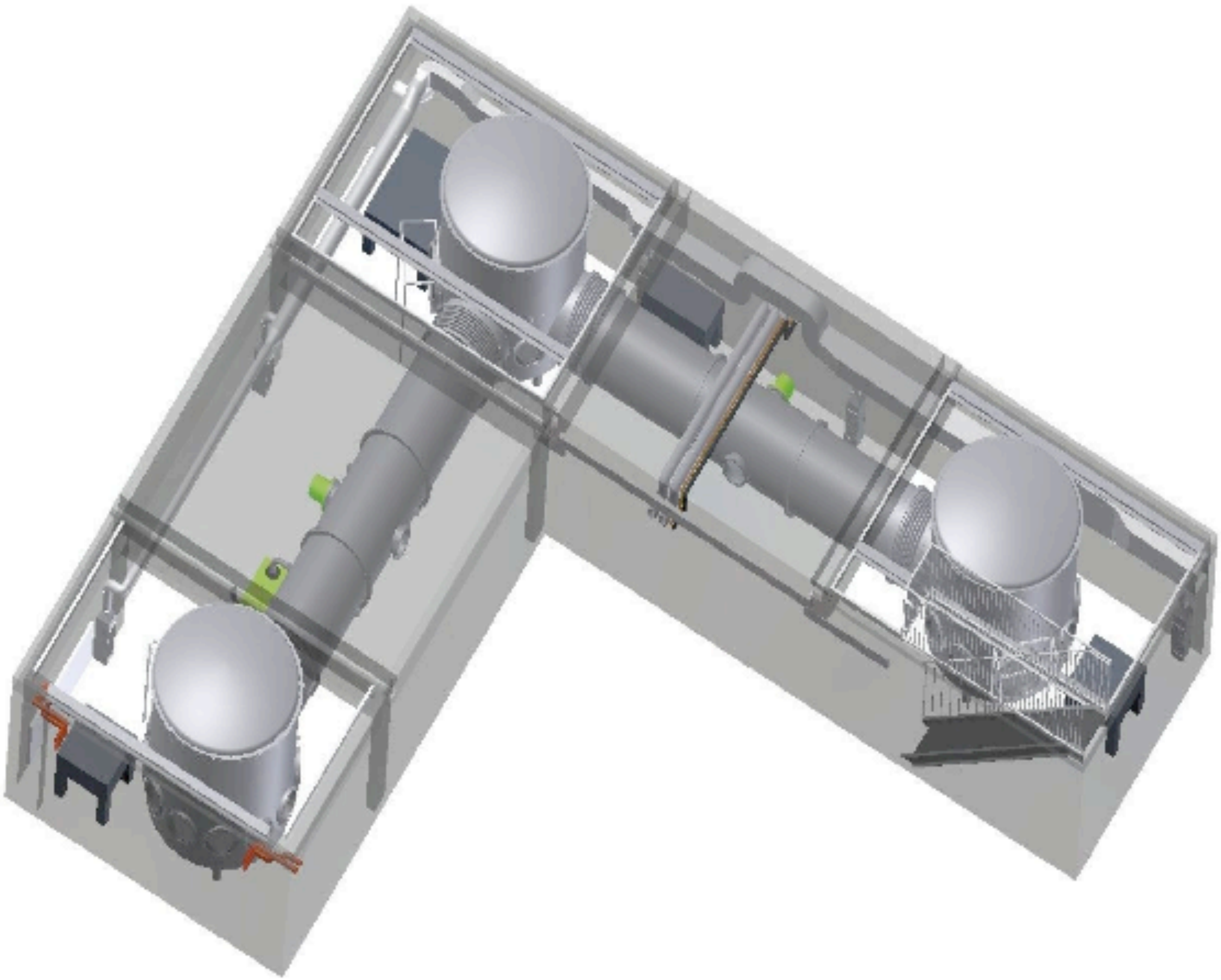
Goals for the Fermilab Holographic Interferometer

1. Measure spatiotemporal cross correlation of displacement to sub-Planck precision
2. Design apparatus to provide convincing evidence for universal Planckian noise, or an upper limit to constrain holographic theories
   - Signatures: frequency spectrum, time domain correlation, modulation by reconfiguring apparatus
   - This has not been attempted before
3. Develop cavity technology at Fermilab for future axion regeneration experiment

Other experiments

- Serious attention from AEI Hannover and Golm (Directors Danzmann, Allen, Schutz)
- Hannover Workshop on Holographic Noise (May 19-20, 2009, AEI): theory and experiment reviewed http://www.aei.mpg.de/~grote/agenda.html
- followup with GEO-600: see talk by Stefan Hild, http://www.aei.mpg.de/~grote/holographic_noise_experiments_GEO600.pdf
- First paper on mystery noise in preparation, likelihood analysis for holographic contribution
- Major modifications to GEO-600 or LIGO impractical
- Possible Hannover followup experiment in 2010+, with signal-recycled cavity design, ~10m scale

The AEI prototype



H. Grote

Science of Holographic Uncertainty

- If noise is not there, constrain interpretations of unified theory:
  - Position wavefunctions include >Planck frequencies
  - Configuration space violates holographic entropy bounds
- If it is detected, explore unification physics in the lab:
  - Evidence for holographic layer
  - 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
  - Fundamental Planck limit on bandwidth, communication

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!
- But experiments might shed light on relevant unification physics

Homework for theorists: partial list

- Clarify relationship of holography to particles and fields
- Create operator formalism for observables
- Calculate cross correlations for general configurations
- Find similar macroscopic limits for string, loop theories
- Estimate higher order corrections
- Estimate holographic effects on particle interactions
- Estimate effect on below-Planck-mass bodies (atom interferometers)
- Calculate effect for other kinds of interferometers, eg, LISA
- Generalize to curved spacetime backgrounds, connect with known holographic duals in eg AdS spacetime
- Analyze basis change of particles in black hole evaporation states
- Find a bulletproof calibration argument from black hole physics