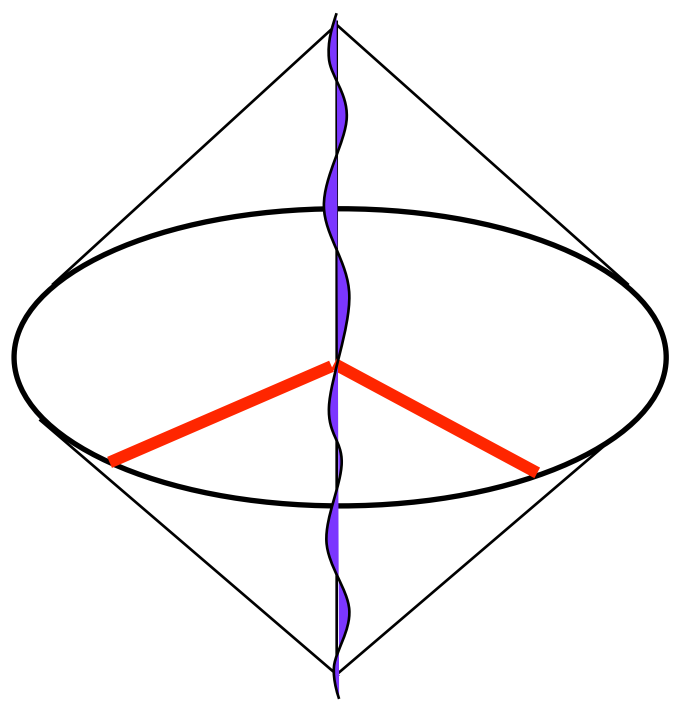
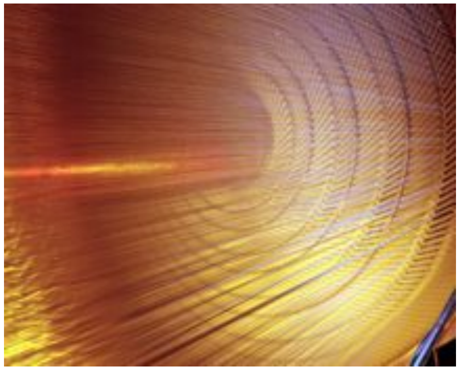
The Fermilab Holometer

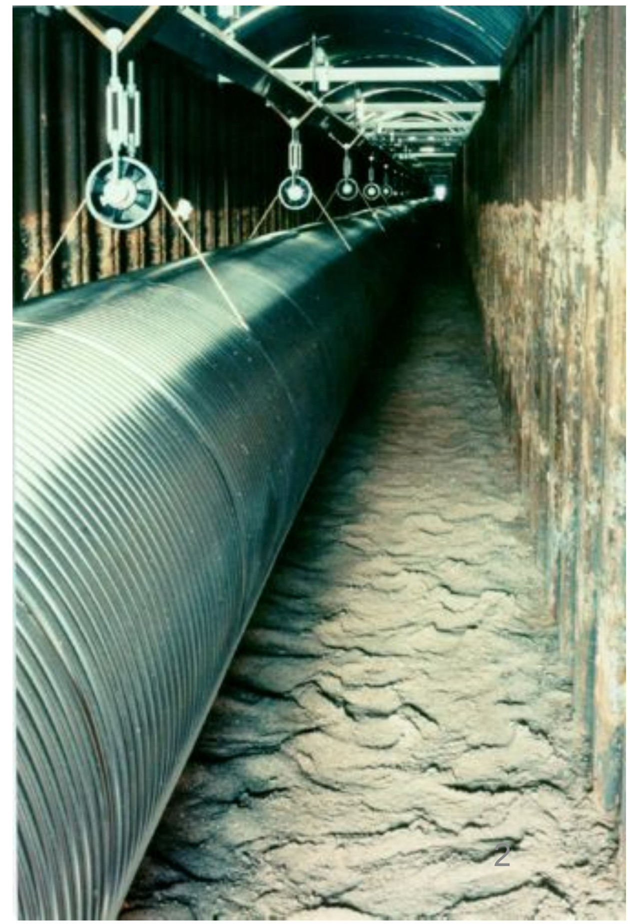
a program to measure Planck scale indeterminacy



Attometer Technologies

Particle colliders: $\mathrm{TeV}^{-1} \sim 10^{-18}$ m: particle interactions





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

Interferometers might sense new unification physics

- Effective theory based on one interpretation of ‘t Hooft-Susskind holographic principle predicts a new detectable effect:

"holographic noise”

- Different from gravitational waves or quantum field fluctuations

- Planck-amplitude spectrum is predicted with no parameters

- It may already be detected

- We propose an experiment to test this hypothesis

Unification: relationship of spacetime to the stuff within it

- Standard physics:
  - Mass-energy: quantum particles/waves follow metric
  - Spacetime: smooth, infinitely divisible, invisible

- New physics of unification:
  - Spacetime and mass-energy both emerge from something different (strings, matrices,…?)
  - Under extreme magnification, spacetime no longer looks like spacetime
  - there is a minimum time/ maximum frequency

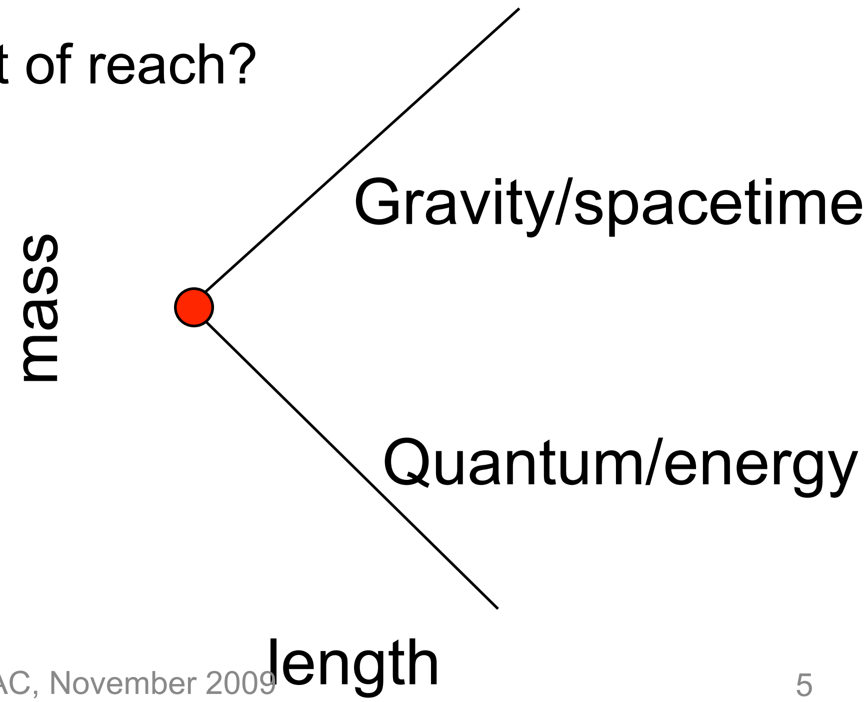
Planck scale: spacetime merges with mass-energy

- Theory suggests a minimum (Planck) time,

$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \text{ sec} \quad (1.5 \times 10^{-35} m)$$

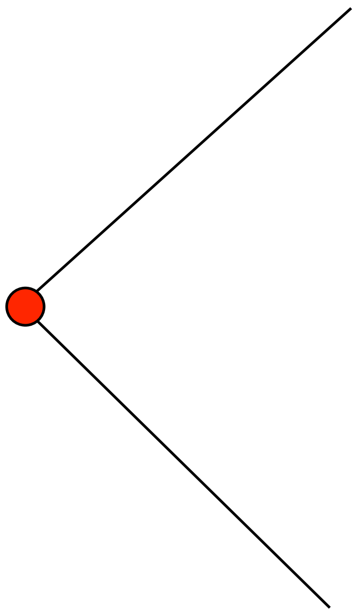
- Particle inside a Planck volume makes its own black hole

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



A new approach to the Planck scale

Mass, energy



position

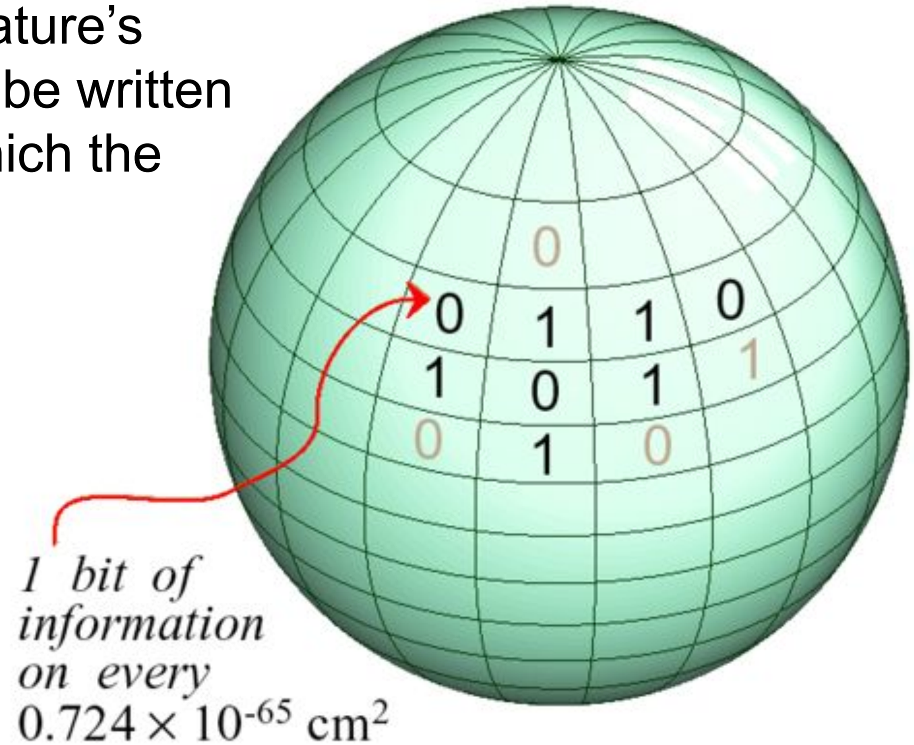
length

momentum

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, with Planck resolution

There has been no experimental test of this conjecture

Holographic unification theory

- Black hole thermodynamics and evaporation
- Universal covariant entropy bound
- Exact state counts of extremal 5D holes
- AdS/CFT type dualities: N-1 dimensional duals
- Matrix theory
- All suggest theory on 2+1 dimensional null surfaces with Planck frequency bound in any frame

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

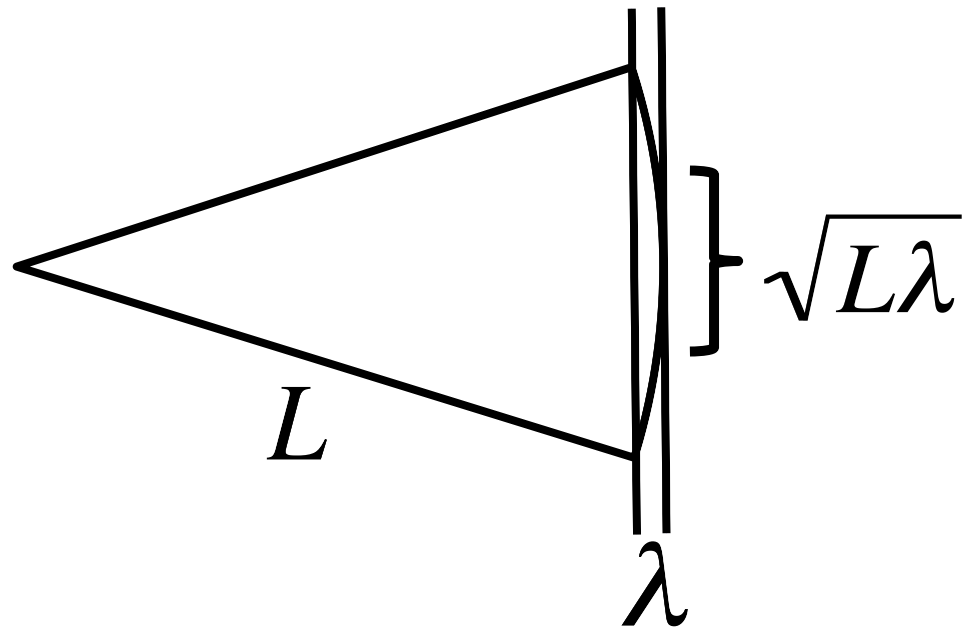
Possible consequences of holography

- Hypothesis: observable correlations are encoded on light sheets and limited by information capacity of a Planck carrier wave ("Planck information flux" limit)

- Leads to uncertainty in position at Planck diffraction scale

- Matter jitters about geodesics defined by massless fields

Transverse position uncertainty at distance *L*



~one radian phase change in Planck wavefront spans a much larger transverse distance

A candidate phenomenon of unified theory

Fundamental theory (Matrix, string, loop,…)

↕

Effective theory (Planck frequency limit, carrier wave, diffractive transverse position uncertainty)

↕

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

Relationships to unified theory

- Known holographic dualities are global (eg, AdS/CFT)
  - local mapping of holographic states is unknown
  - macroscopic limit in nearly-flat space is unknown
  - We test one conjecture about how it might work

- Matrix theory on light sheets
  - One interpretation yields a 2+1D Planck wave equation for position

- Black hole evaporation/entropy
  - calibrates information capacity of a light sheet
  - calibrates fundamental frequency

Survey of theoretical background: **arXiv:0905.4803**

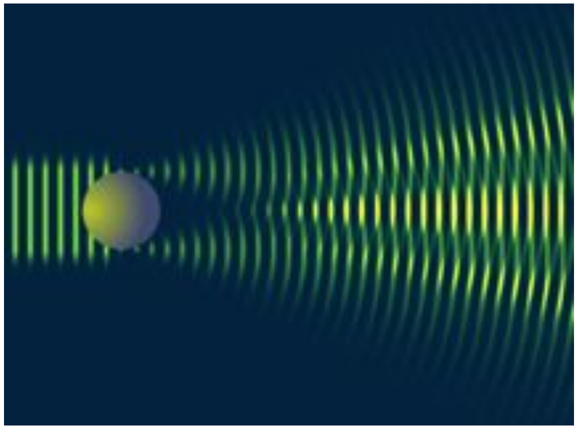
- Arguments for the new indeterminacy
  - Information bounds, black hole evaporation, matrix theory

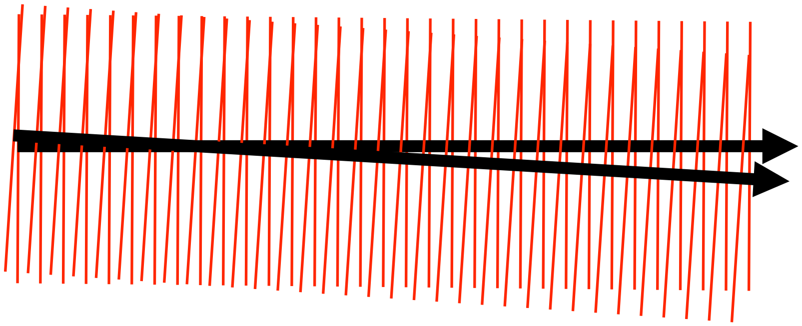
- Arguments for spatial coherence of jitter
  - Locality, isotropy, light-sheet interpretation of matrix theory

- Ways to calculate the noise
  - Wave optics
  - Planck wavelength interferometer limit
  - Precise calibration from black hole entropy

- No argument is conclusive: motivation for an experiment!

Indeterminacy of a Planckian path





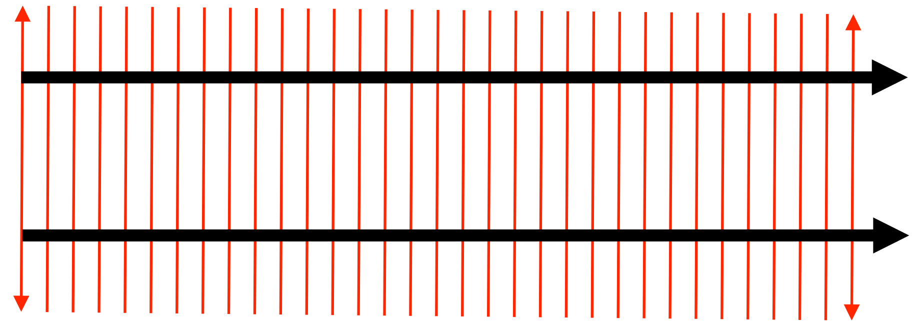
Classical spacetime manifold defined by paths and events

Classical path ~ ray approximation of wave

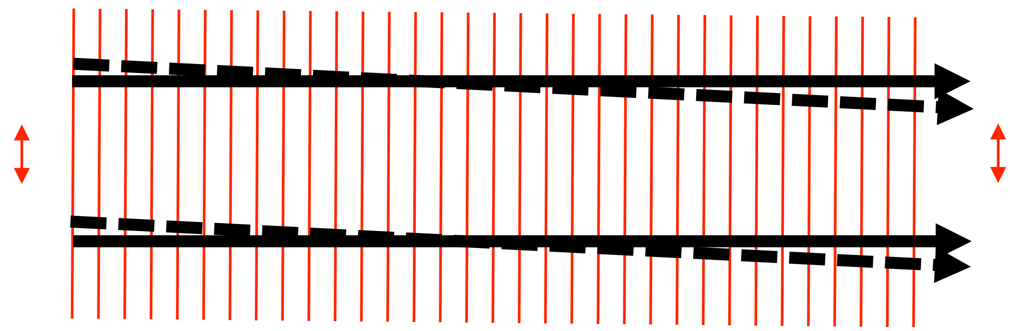
Indeterminacy of rays reflects Planck information flux limit

“Nature: the ultimate internet service provider”

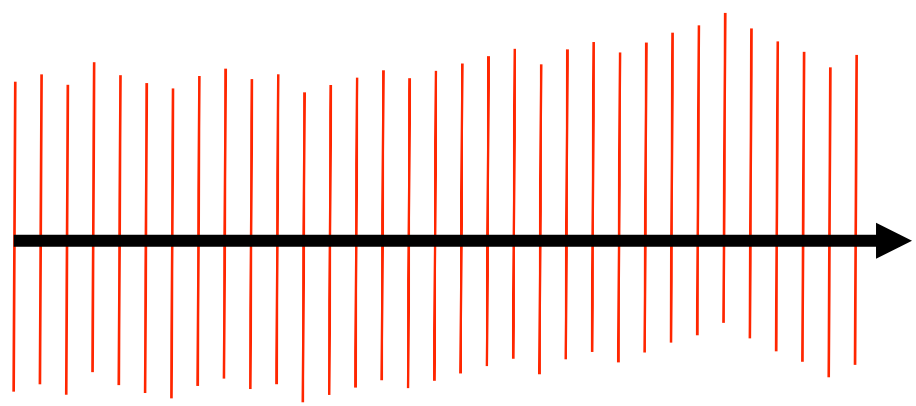
Rays in direction normal to Planck wavefronts



Localize in wavefront: transverse momentum, angular uncertainty



Interpret as wavefunction of position: transverse Planck random walk

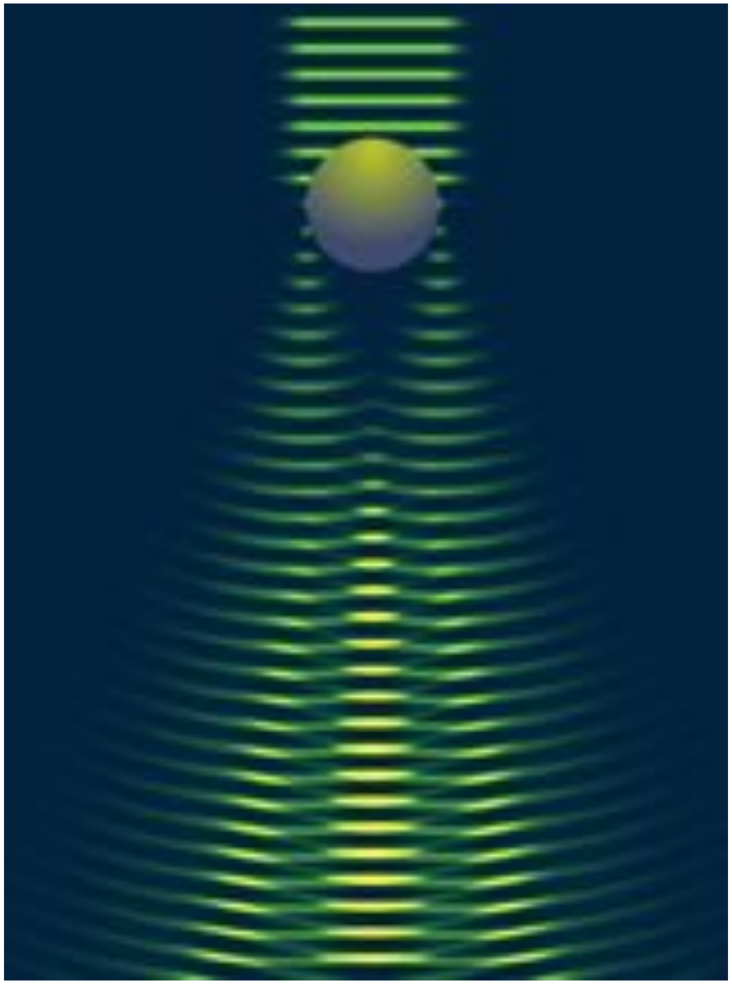


Wave Theory of Spacetime

Adapt wave optics to theory of "spacetime wavefunctions"

Transverse indeterminacy from interference of Planck waves

Allows calculation of observable correlation and holographic noise with no parameters



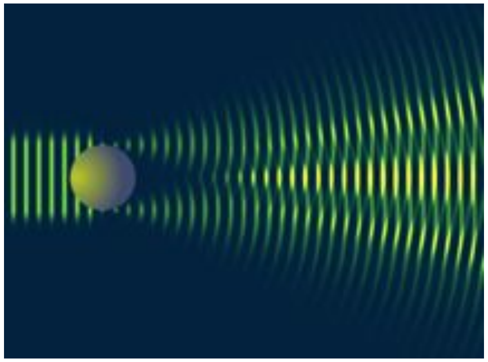
Approach to the classical limit

Angles become **less uncertain** (more ray-like) at larger separations:

$$\Delta\theta^2 > l_P / L$$

Transverse positions become **more uncertain** at larger separations:

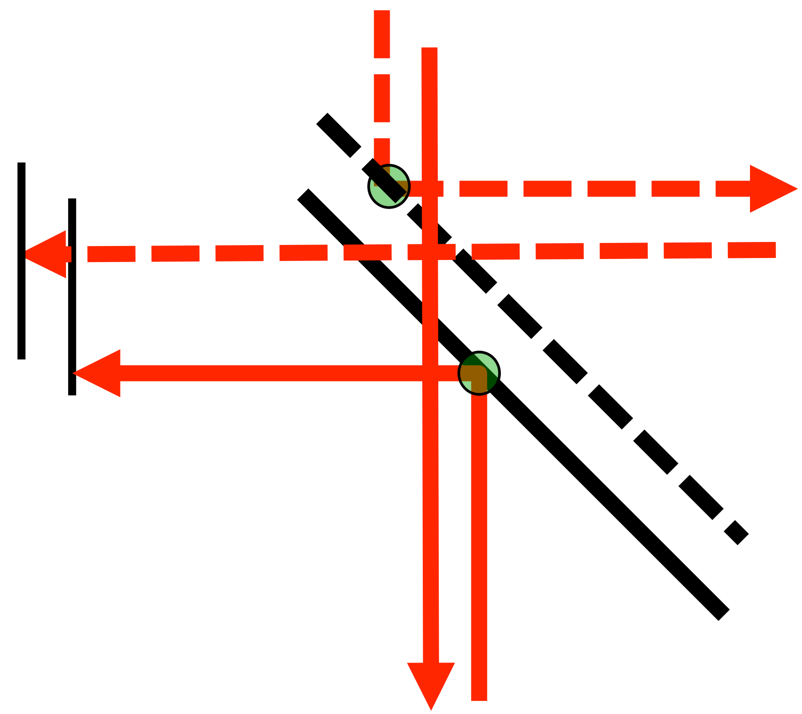
$$\Delta x^2 > l_P L$$



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

Holographic noise in a Michelson interferometer

Jitter in beamsplitter position leads to fluctuations in measured phase



this is a new effect predicted with no parameters

Universal Flat Holographic Noise Spectrum

Strain amplitude spectral density independent of frequency:

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

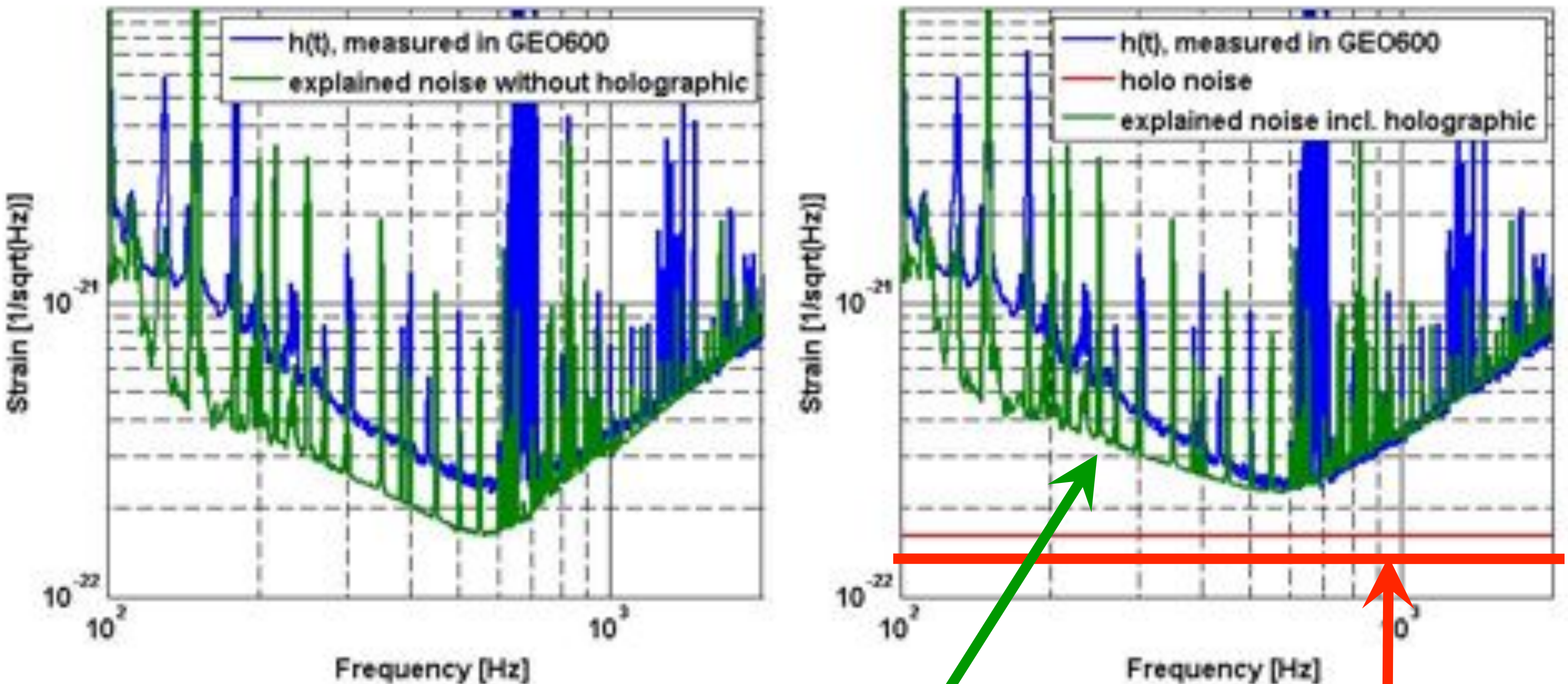
Exact spectrum depends on the apparatus

For Michelson with *N* folds in low frequency limit it is

$$\mathcal{N}^{-1} 2 \sqrt{t_P/\pi} = \mathcal{N}^{-1} 2.6 \times 10^{-22} / \sqrt{\mathrm{Hz}}$$

GEO-600 (near Hannover, Germany)

"Mystery Noise" in GEO600



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

Data: S. Hild (GEO600)

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

Total noise: not fitted

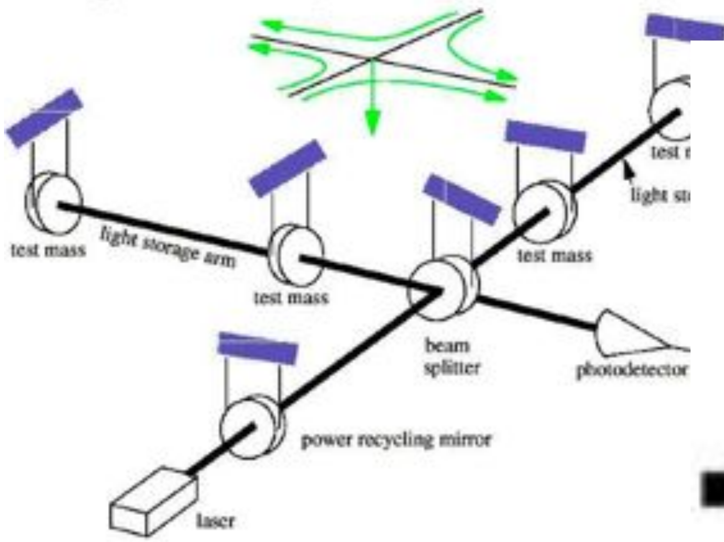
zero-parameter prediction for holographic noise in GEO600 (strain amplitude spectrum)

Why doesn't LIGO detect holographic noise?

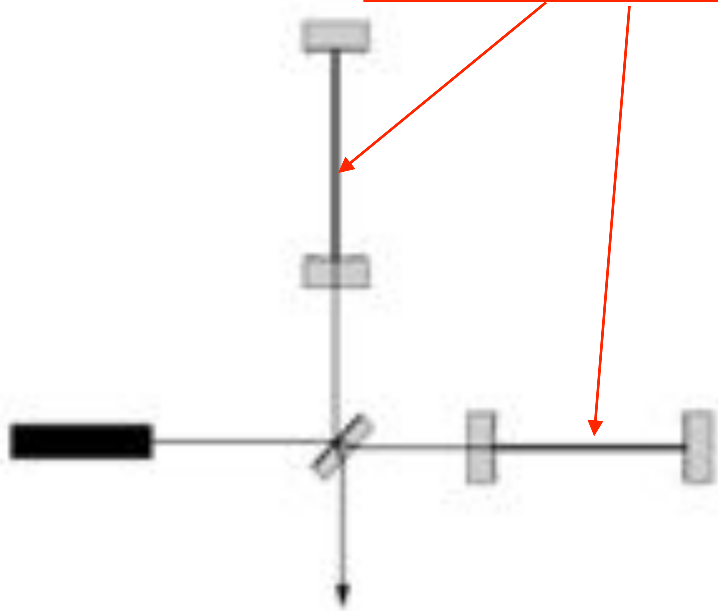
LIGO design is less sensitive than GEO600 to transverse displacement noise, but more sensitive to gravitational waves

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



Interferometers may detect Planckian noise

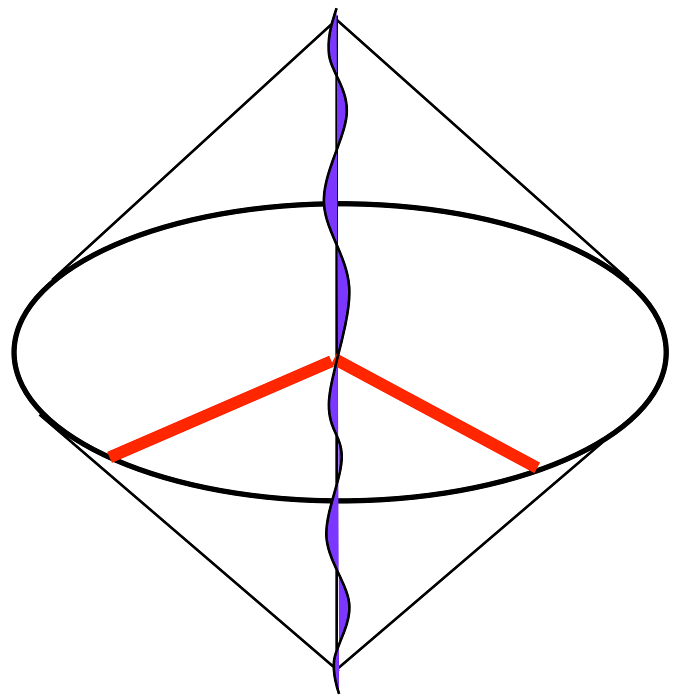
- Beamsplitter position indeterminacy inserts holographic noise into signal
- **system with GEO600 technology can detect holographic noise if it exists**

CJH: arXiv:0712.3419 Phys Rev D.77.104031 (2008)
CJH: arXiv:0806.0665 Phys Rev D.78.087501 (2008)
CJH & M. Jackson: arXiv:0812.1285 Phys Rev D.79.12400 (2009)
CJH: arXiv:0905.4803

Current experiments: summary

- Most sensitive device, GEO600, sees unexplained noise compatible with holographic prediction
- GEO600 paper in preparation after ~2 years of checking
- Very recently: mystery noise at $f < 300$ Hz explained with improved instrument (does not affect holographic part)
- LIGO: wrong configuration to study this effect
- No experiment has been designed to look for holographic noise
- A definitive result is difficult with GEO600: evidence is based on noise model
- More convincing evidence: new apparatus, designed to eliminate systematics of noise estimation

The Fermilab Holometer



Holographic Interferometer: “Holometer”

1696: “a Mathematical Instrument for the easie measuring of any thing whatever”

Entry printed from *Oxford English Dictionary Online*

holometer

SECOND EDITION 1989

(həʊˈlɒmɪtə(r)) [f. HOLO- + -METER, Cf. F. *holomètre* (1690 Furetière), ad. mod.L. *holometrum*, f. Gr. ὁλο- HOLO- + μέτρον measure.]

A mathematical instrument for making all kinds of measurements; a pantometer.

> **1696** PHILLIPS (ed. 5), *Holometer*, a Mathematical Instrument for the easie measuring of any thing whatever, invented by Abel Tull. **1727-41** CHAMBERS *Cycl.* s.v., The holometer is the same with what is otherwise denominated *pantometer*. **1830** *Mech. Mag.* XIV. 42 To determine how far the holometer be entitled to supersede the sector in point of expense, accuracy or expedition.

Goals of the Fermilab Holometer

1. Measure spatiotemporal cross correlation of displacement in two interferometers to sub-Planck precision
2. Design apparatus to provide convincing evidence for universal holographic noise, or an upper limit well below Planck amplitude
   - Signatures: frequency spectrum, time domain correlation, modulation by reconfiguring apparatus
   - This has not been attempted before
   - Tests a precise hypothesis and predictions, including holographic macroscopic correlation
   - “key under the lamppost” unification experiment
3. Overlaps with ongoing cavity technology development at Fermilab for future axion regeneration experiment

Holographic noise in nearby interferometers is correlated

- Matter on a given null wavefront “moves” together
  - No locally observable jitter should depend on remote measurements

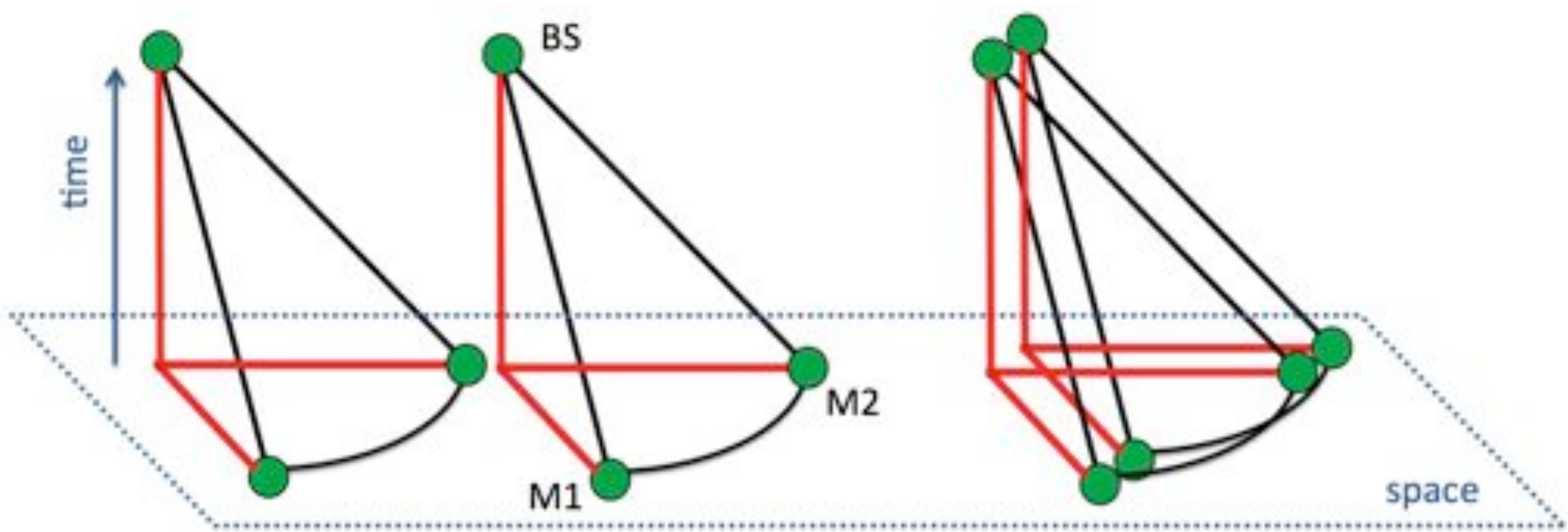
- Spacelike separated measurements within causal diamond must collapse into the same quantum state

- Displacements in nearby interferometers are nearly the same

- This is key to the design

Nearby interferometers: overlapping spacetime volumes, correlated holographic noise

Nonoverlapping spacetime volumes, uncorrelated noise

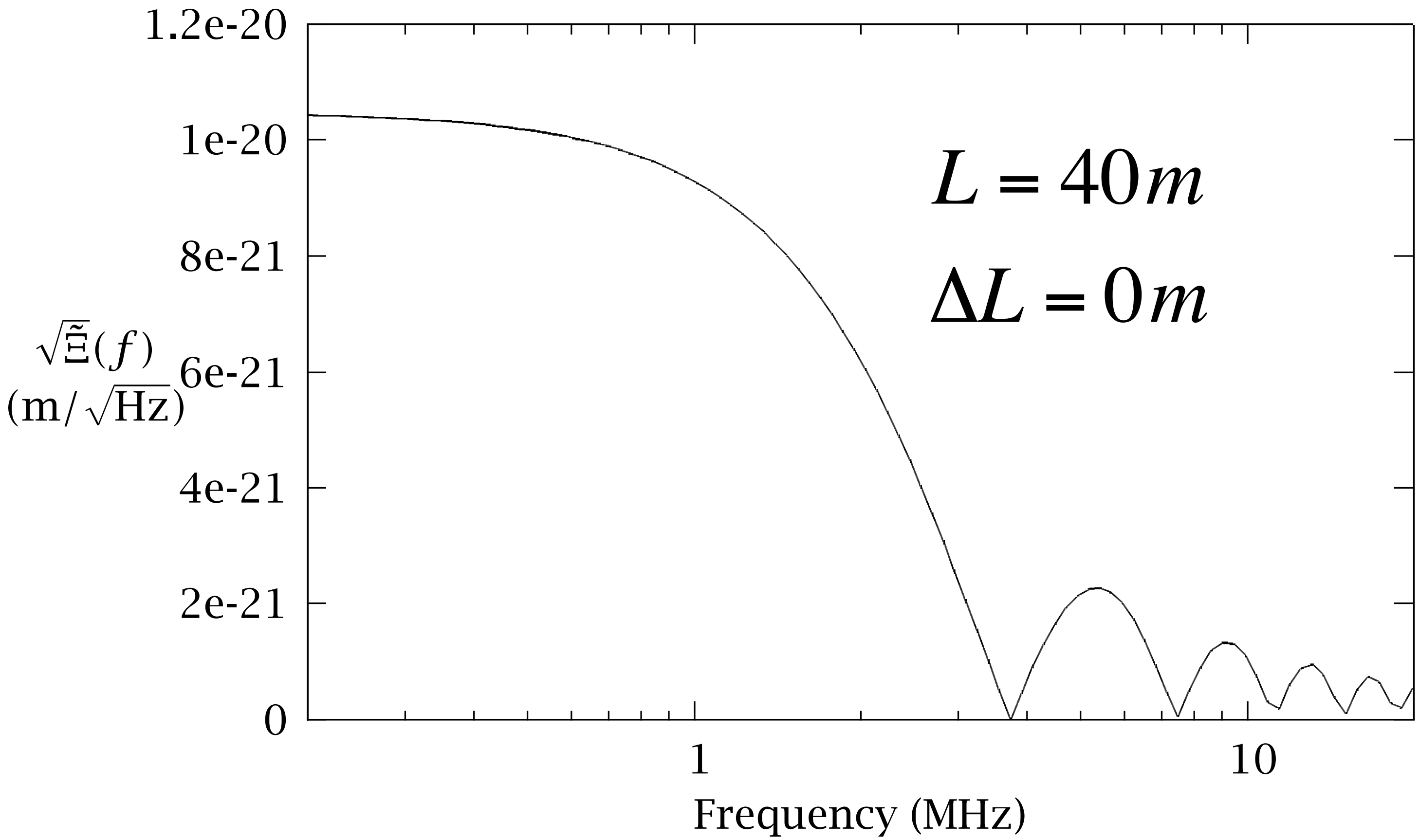


Conceptual Design of Fermilab Holometer

- Two ~40m power-recycled Michelson interferometers
- Cross correlate signals
- ~2 W lasers, ~2000 W cavities
- sampling at ~20MHz, main signal at ~few MHz
- Simple mounts, optics
- holographic noise= laser photon shot noise in ~3 minutes
- Signature: known spectrum and amplitude
- Test: modulate correlation by moving devices

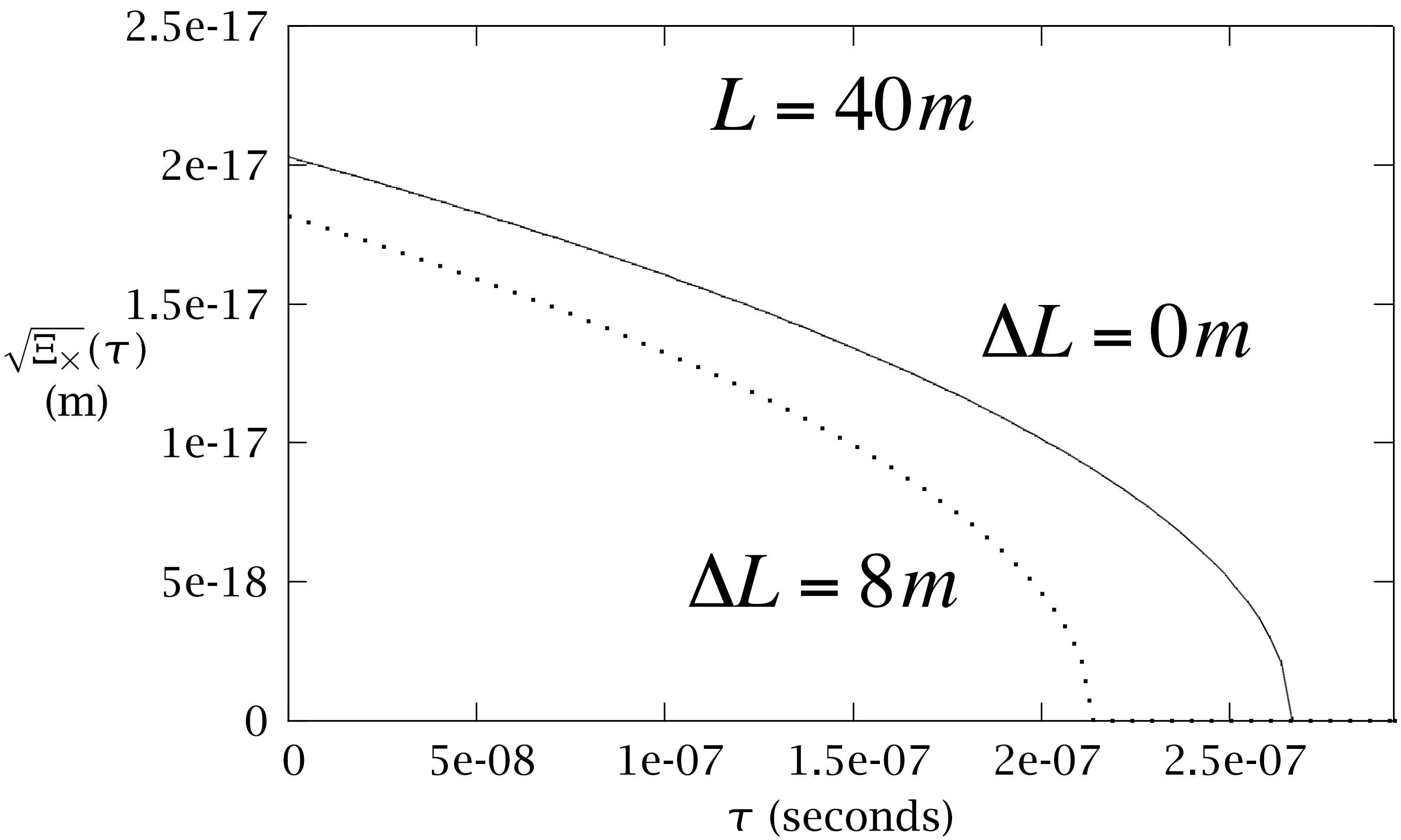
Precise target: predicted frequency spectrum

$$\tilde{\Xi}(f) = \frac{c^2 2 t_P}{\pi (2\pi f)^2}[1 - \cos(f/f_c)], \qquad f_c \equiv c/4\pi L$$



Predicted time-domain cross correlation, decorrelation

$$\Xi_\times(\tau) \approx (\lambda_P/\pi)(2L - 2\Delta L - c\tau), \qquad 0 < c\tau < 2L - 2\Delta L$$
$$= 0, \qquad c\tau > 2L - 2\Delta L.$$



Main noise at high frequency: photon shot noise

Time for one sigma detection of holographic signal:

$$t_{\rm obs} > \left(\frac{h}{P_{\rm BS}}\right)^2 \left(\frac{\lambda_{\rm opt}}{\lambda_{\rm Pl}}\right)^2 \left(\frac{c^3}{32\pi^4 L^3}\right)$$

For our parameters, time for three sigma is ~ 30 minutes

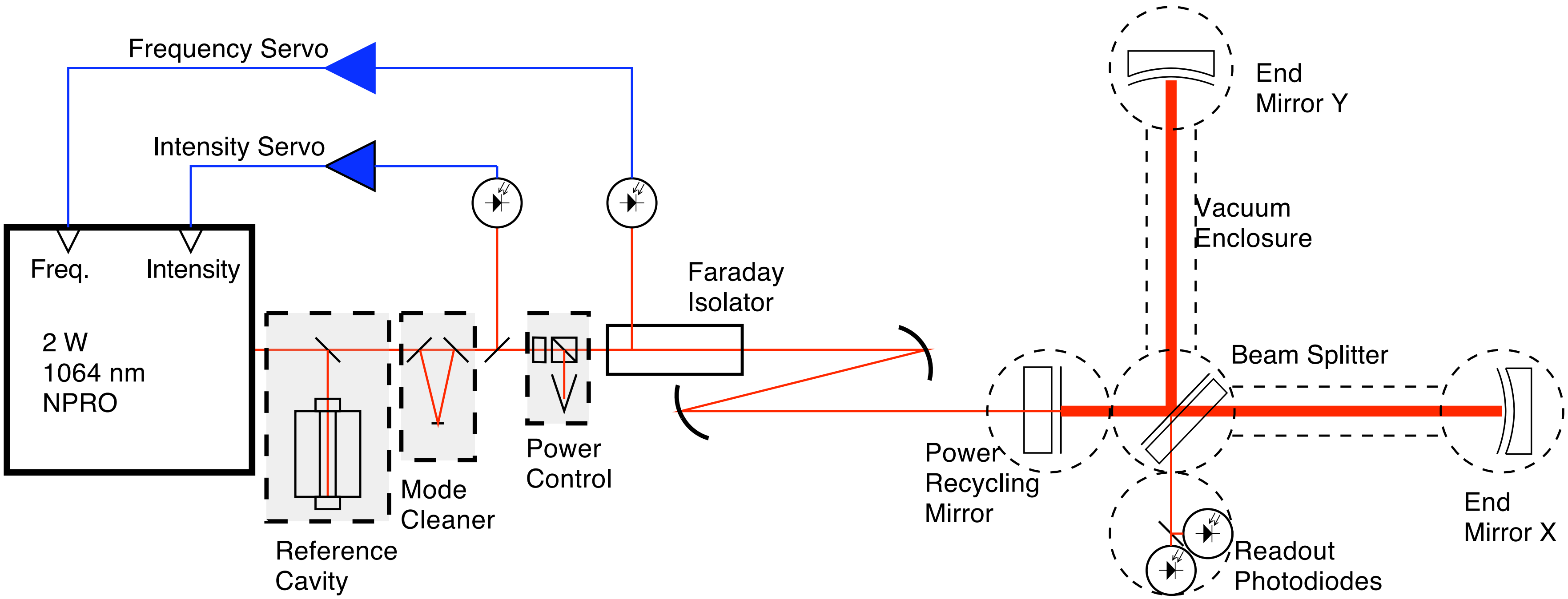
Interferometer design informed by LIGO experience

- Simple optical design
  - Simulation software well tested in LIGO and prototypes
  - Much experience with noise sources for a single system
- Well tested components
  - Mirrors: specifications in routine range for known vendors
  - Mounts: likely solid, possible migrate to suspensions
  - Detectors: modified commercial photodetectors
  - Baffles: LIGO design, inserted into beam tubes

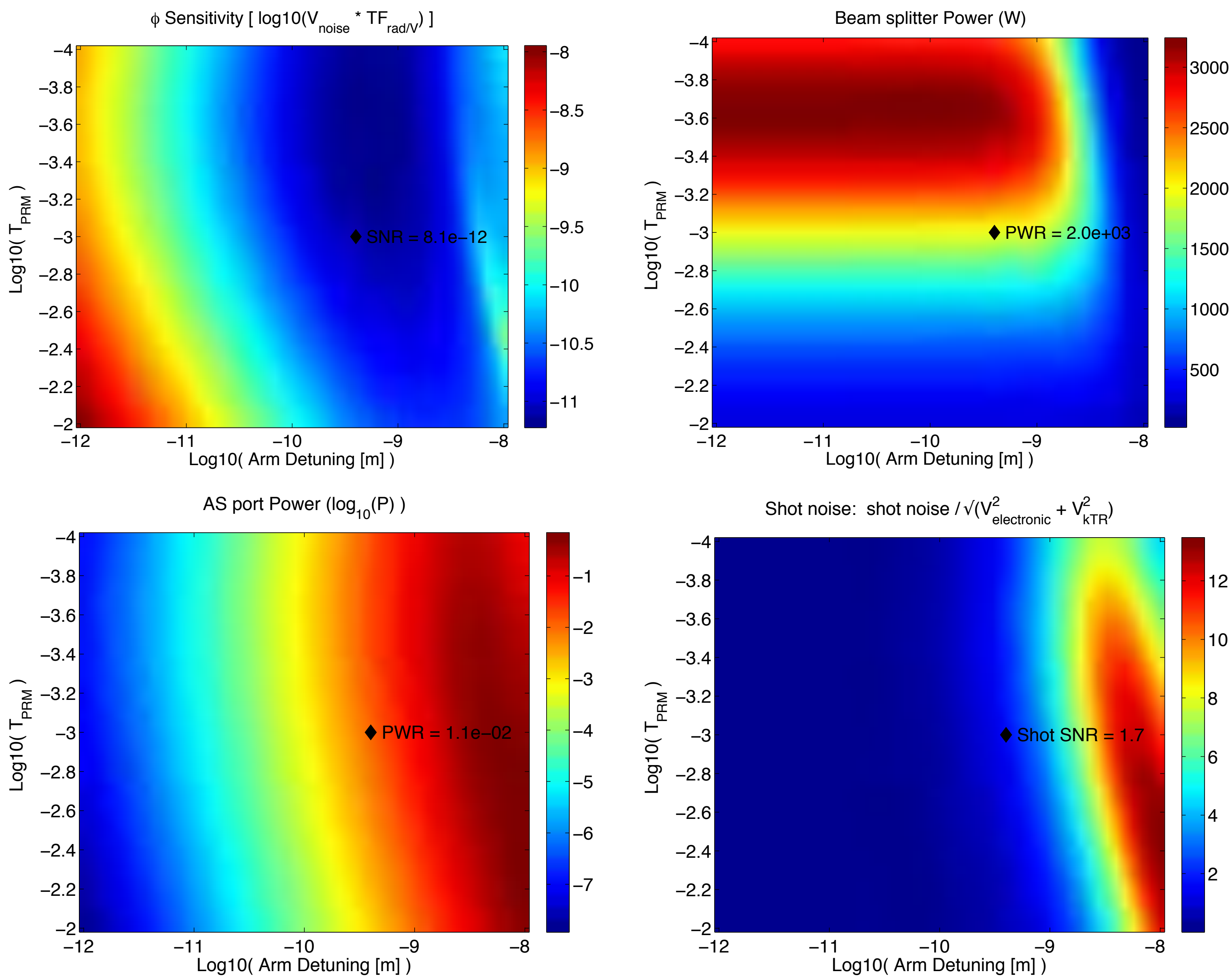
New features

- High frequency cross correlation little explored
- Electronics designed to diagnose interference
- Systems designed for isolation, mobility

Optical layout: standard power-recycled Michelson



Optimize optical parameters of the cavity



Vacuum system:

~ 10^{-6} Torr

Fast pump down

access, mobility

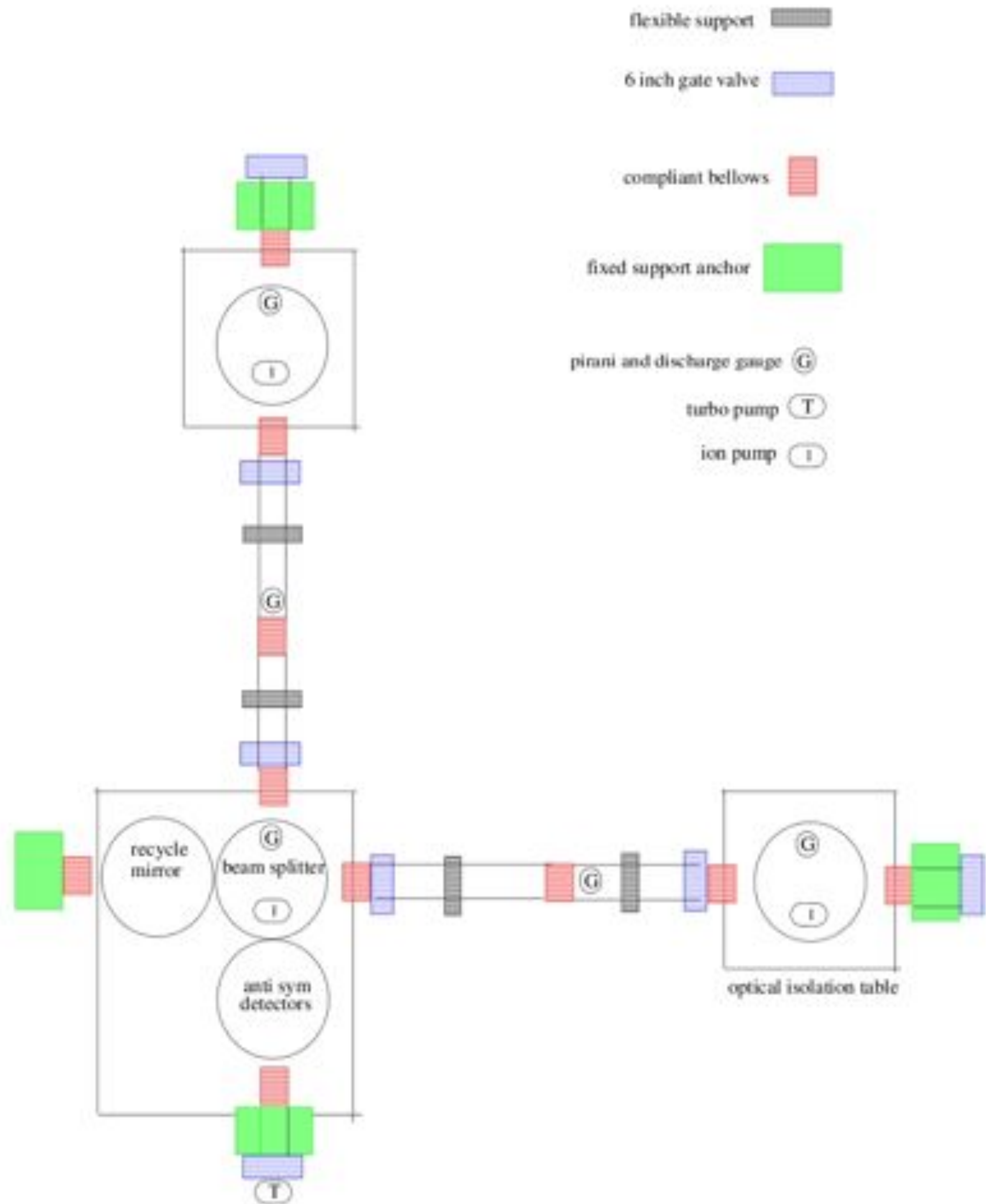
Clean 304 steel

6 in diameter, 10 foot tubes

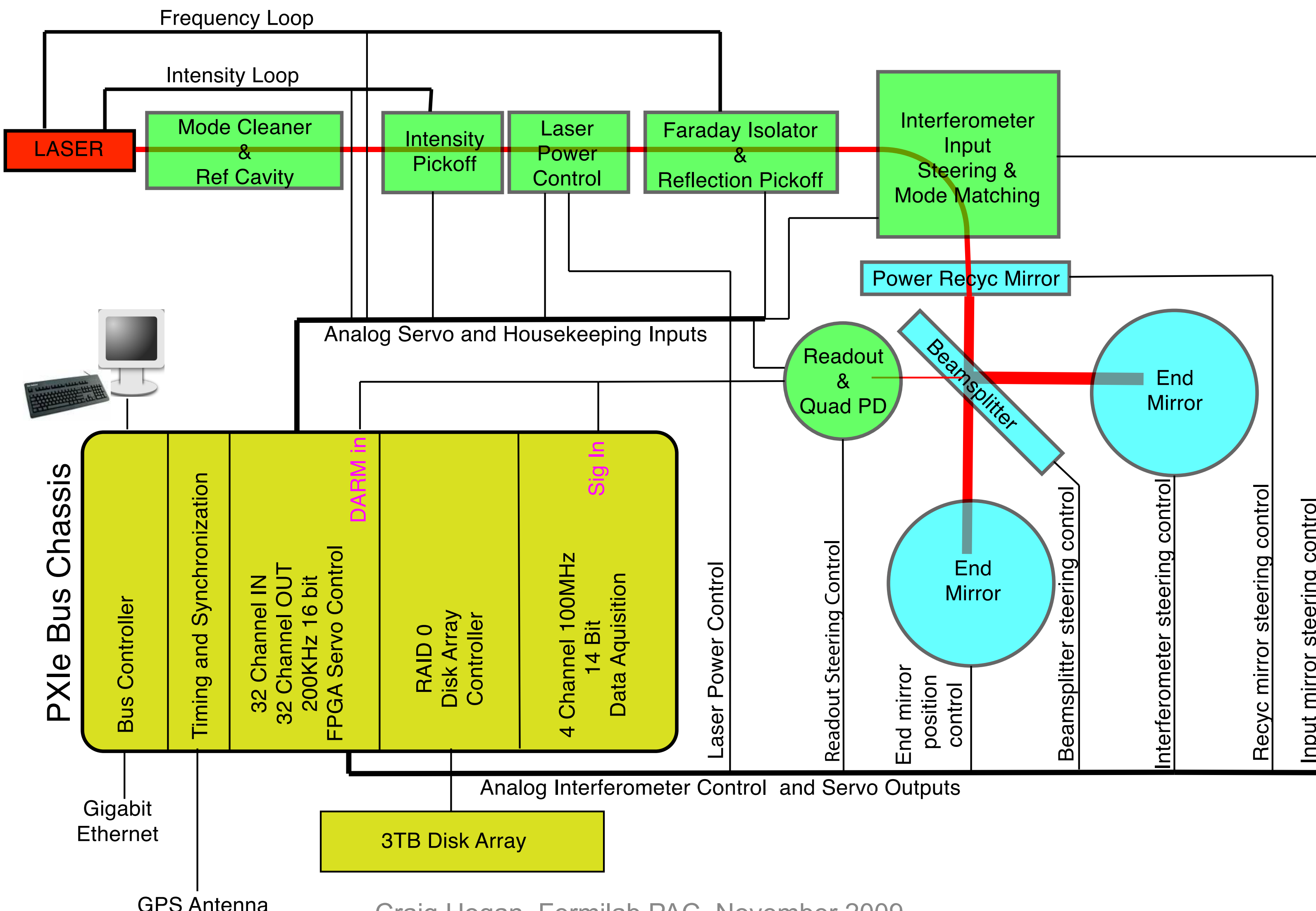
24 in vacuum vessels

standard and semi-custom components

Bid in hand



Electronics: system from off-the-shelf components being built at University of Chicago



Data

- High SNR in ~ 1 hour
- 6 Tb total per 10 hour run
- Whole dataset does not need archiving
- Relevant correlation and housekeeping data compresses to ~40Gb per 10 hour run
- ~tens of Tb for whole project

Other elements

- optical tables, vibration isolation (commercial)
- standard portable clean rooms
- 40m by 80m space
    - warehouse lease: fast, flexible
- Seismic stability: pre-occupancy survey

Schedule

Task	Design ongoing until March, 2010	Construction March 2010 - June 2010
DAC System	purchase one system; 4 weeks lead time	purchase second system; 4 weeks lead time
Laser Table Optics	small table training and development; 12 weeks	purchase; 4 week lead time
Interferometer Optics	”	purchase; 10 week lead time
Intensity and Frequency Servos	”	
Operations Site Computing	requirements analysis and implementation plan; 2 weeks	purchase; 1 month lead time
Fermilab Computing	analyze disk/tape/robot options; 2 weeks	
Vacuum Vessels and Tubes	vet design; 8 weeks	purchase; 10 weeks lead time
Vacuum Pumps and Instrumentation	”	”
Support Stands	design; 2 weeks	fabricate; 8 week lead time
Baffles	design and prototype; 7 weeks	fabricate; 4 week lead time
Laser Table (mechanical)	design; 2 weeks	fabricate baffle; 4 week lead time
Portable Clean Room		purchase; 6 week lead time
Safety	review laser and vacuum design and operations plans; 1 week	
Warehouse	8 weeks specify	8 weeks bid and approve

M&S costs

Task	Design	Construction	Operations
DAC System	$54K	$54K	
Laser Table Optics	$140K	$140K	
Interferometer Optics		$68K	
Intensity and Frequency Servos	$32K	$32K	
Operations Site Computing		$40K	
Fermilab Computing			$70K for 70 TByte
Vacuum Vessels and Tubes		$250K	
Vacuum Pumps and Instrumentation		$175K	
Baffles		$10K	
Portable Clean Room		$48K (Terra Universal web)	
Support Stands		$30K	
Laser Table (mechanical)		$120K	
Safety		$10K (goggles, partitions, interlocks)	
Warehouse			$900K
TOTAL	$226K	$977K	$970K

Non-scientist effort

Task	Design	Construction	Commissioning (6 months)	Measurement
DAC System				
Laser Table Optics	1.00 EP	1.00 EP	1.00 EP	
Interferometer Optics				
Optics Mounts				
Intensity and Frequency Servos	2.00 EE; 0.50 MT	4.00 ET	0.50 ET	
On Site Computing	0.25 CP		0.25 CP	
Off Site Computing	0.25 CP			
Vacuum Vessels and Tubes	0.25 ME		1.00 MT	continuing 0.25 FTE MT
Vacuum Pumps and Instrumentation	0.25 ME		1.00 MT	continuing 0.25 FTE MT
Support Stands	0.25 ME		1.00 MT	
Baffles	1.00 ME		1.00 MT	
Laser Table (mechanical)	0.25 ME		1.00 MT	
Portable Clean Room			1.00 MT	
Safety				
Warehouse				continuing 0.5 FTE MT
TOTAL non scientist FTE months	6.0	5.00	7.75	continuing 1.0
Cost w/OPTO/vac/fringe/overhead	$98k	$58k	$84k	$297k

Table 9: FTE months non scientist effort: CP=computing professional; MT=mechanical tech; EE=Electronics Engineer; ET=Electronics tech; ME=mechanical engineer; EP=engineering physicist. The FTE cost uses PPD rates for FY2009 inflated by 3%, with OPTO, vacation, fringe, and overhead included.

Budget summary

- Design phase: $226K M&S + $96K non-scientist effort

- Construction phase: $977K M&S + $58K non-scientist effort
  - Total construction with 50% contingency: $1.55M

- Operations for 3 years: $970K M&S + $381K non-scientist

- Closed-ended program to achieve goals
  - Null result could be achieved sooner

- Scientist team: ~4 FTE for ~ 4 years

Status of the Fermilab Holometer

- Team:
  - Fermilab (A. Chou, G. Gutierrez, CJH, E. Ramberg, J. Steffen, C. Stoughton, R. Tomlin, W. Wester, others TBD)
  - MIT (R.Weiss, S.Waldman)
  - Caltech (S. Whitcomb)
  - University of Chicago (S. Meyer)
  - University of Michigan (R. Gustafson)
  - includes LIGO experts
- Building tabletop prototypes at Fermilab since June
  - Successful edge-locked interferometer
  - Successful power recycled cavity
- Designed 40m system
- After Director approval: DOE Field Work Proposal

Science of Holographic Noise

- If noise is not there, constrain interpretations of holography:
  - Position wavefunctions include > Planck spatial frequencies; or
  - Spatial relationships better defined than black hole entropy bound; or
  - Spatial coherence is misinterpreted
  - But no direct challenge to widely cherished beliefs
- If it is detected, explore unification physics in the lab:
  - Measure all physical degrees of freedom
  - 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
  - Planck limit on bandwidth, communication

June 2009 PAC letter

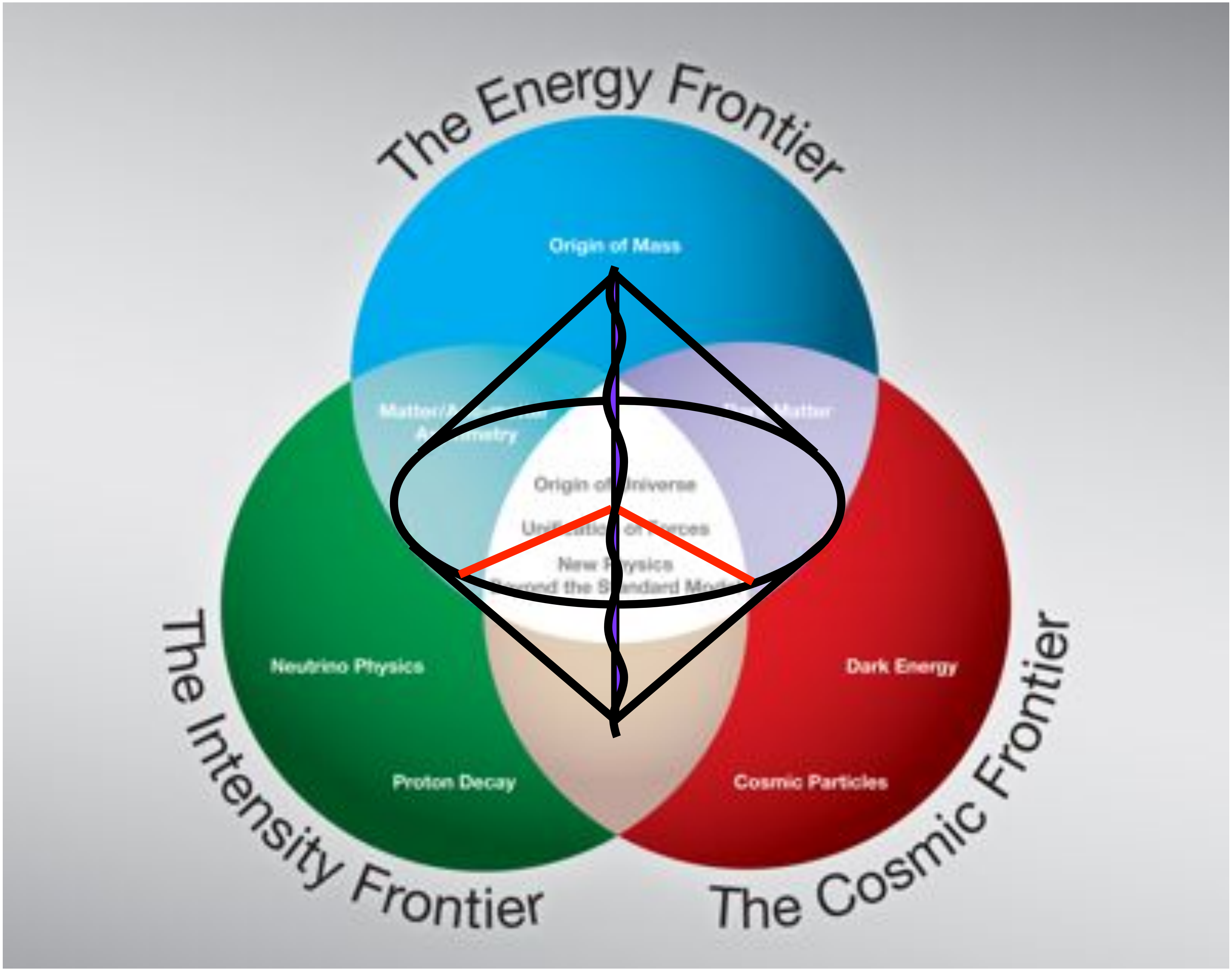
"*Build a broader understanding in the theoretical and experimental community of the soundness of this approach and of the significance of the experimental results. Questions that should be widely addressed include:"*

1. "*How generic is this prediction?"*
   - Derived from very general principles, but no fundamental theory
2. "*Is the idea already excluded by other constraints?"*
   - No.
3. *"What would we learn from a negative result?"*
   - "position state correlations exceed Planck information flux"
   - Next question, still unanswered, would be: "So what?"
4. *"Can the effect be excluded by GEO600 in the near future?"*
   - Probably not conclusively
5. *"What sensitivity goals should be pursued in a more general framework?"*
   - After significant exclusion of Planck level predicted noise, the program should terminate; laser work should migrate to axion cavities

June 2009 PAC letter (cont.)

"*Through a critical review with external experts (both theorists and experimentalists), establish the feasibility of the proposed experiment to provide definitive results. Among other issues, an important design challenge is to ensure that common-mode noise between two close-by interferometers would be under control.*"

This mini-review's report will provide expert input to the PAC and the Directorate


The Energy Frontier
Origin of Mass
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier