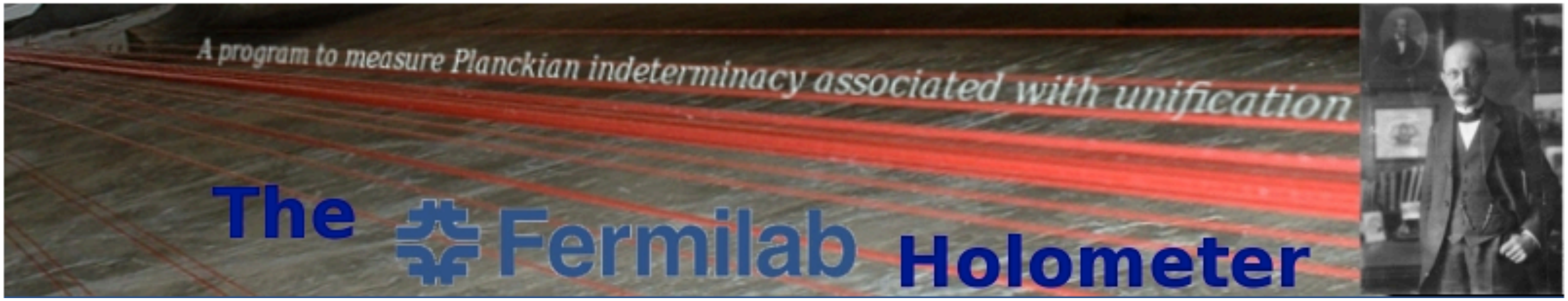
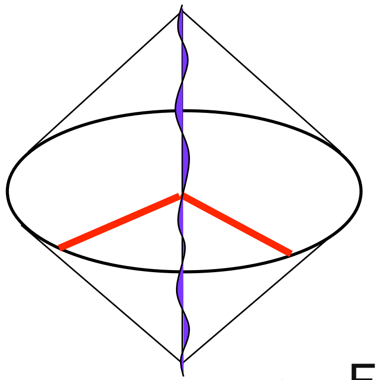


Search for Planck-Suppressed Position Noise in Interferometers

Aaron S. Chou
Fermilab

March 6, 2013



The Holometer (Fermilab E-990):

Interferometer probe of the quantum structure of space-time at the Planck scale 10^{19} GeV

- Fermilab:
  - A. Chou (co-PI, project manager), H. Glass, C. Hogan, C. Stoughton, R. Tomlin, J. Volk, W. Wester.
- U.Chicago
  - S. Meyer (co-PI), R. Lanza, L. McCuller, J. Richardson
- MIT LIGO:
  - M. Evans, S. Waldman, R. Weiss
- U. Michigan LIGO
  - D. Gustafson
- Northwestern
  - J. Steffen
- Vanderbilt
  - B. Kamai

Training 4 PhD students, and providing research experience to numerous undergrads (including 3 senior theses), and high school students

Science goals of Holometer

DOE OHEP Mission Statement:

The mission of the High Energy Physics program is to understand how our universe works at its most fundamental level. We do this by discovering the most elementary constituents of matter and energy, exploring the basic nature of space and time itself, and probing the interactions between them. These fundamental ideas are at the heart of physics and hence all of the physical sciences. To enable these discoveries, HEP supports theoretical and experimental research in both elementary particle physics and fundamental accelerator science and technology. HEP underpins and advances the DOE missions and objectives through this research, and by the development of key technologies and trained manpower needed to work at the cutting edge of science.

- **The Holometer will search for Planck-suppressed position noise which is predicted to be intrinsic to the quantum structure of space-time.**
  - **If such noise is absent, the Holometer will conclusively exclude the holographic noise model.**
  - **If the noise is present, the Holometer will test the predicted properties of the noise spectrum.**
- **The Holometer will also perform a sensitive search for gravitational waves at MHz frequencies, e.g. from local decay of cosmic strings**

Holometer Status

2009-2010: R&D stage funded from DOE KA15, Fermi Research Associates, NASA, U.Chicago funds

2011: Construction/operations funded by DOE KA13 via Early Career Award

2012: Two 40m interferometers deployed and operational.

2013: Commission full-power operation of interferometers, **begin noise hunt!**

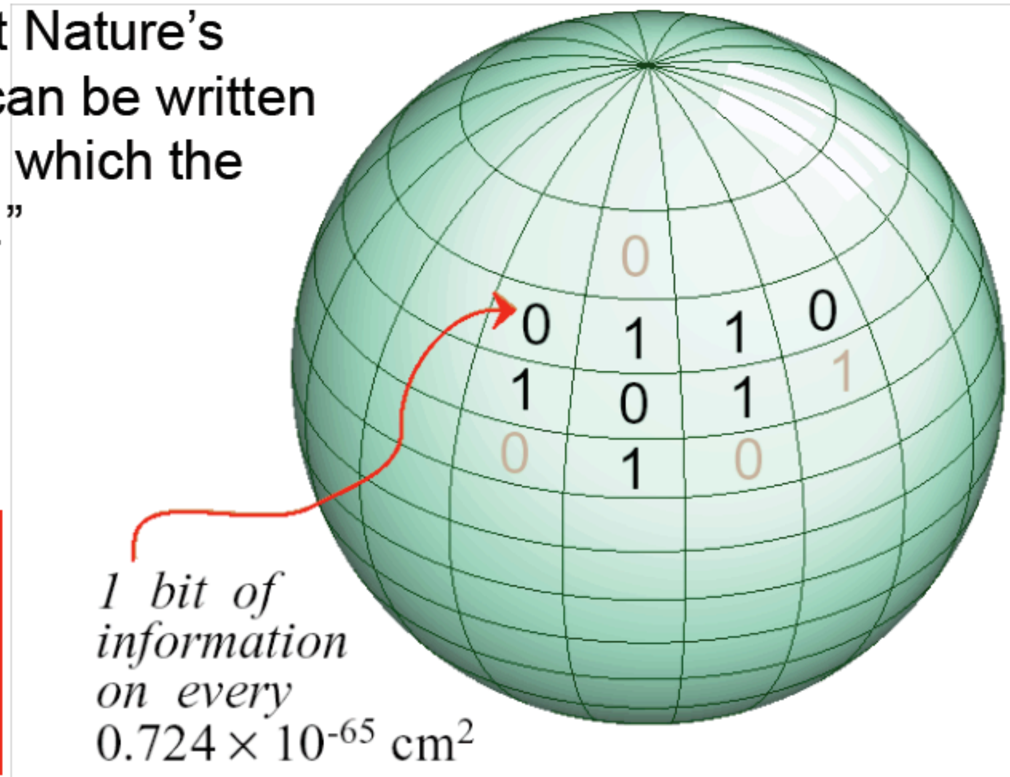
Bekenstein-Hawking black hole entropy suggests that our world is holographic

Susskind, ‘t Hooft

$$S_{BH} = A_{BH} \times (M_{pl}/2)^2 = A_{BH}/(2\ \lambda_{pl})^2$$

“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

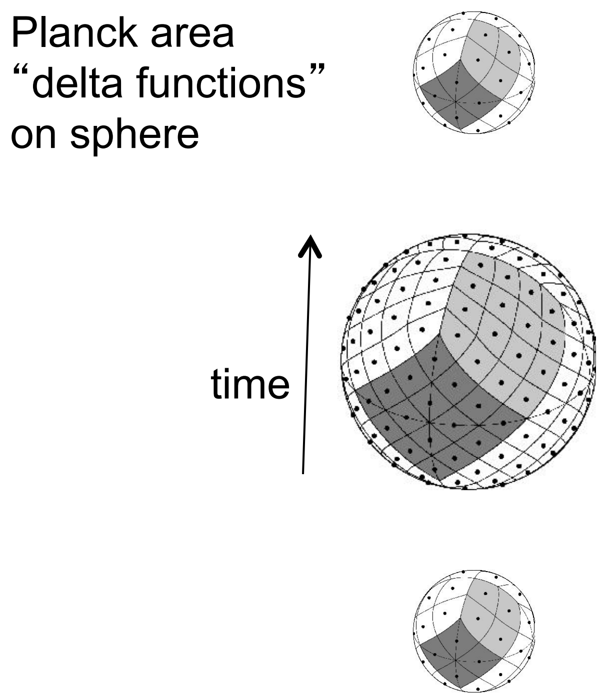


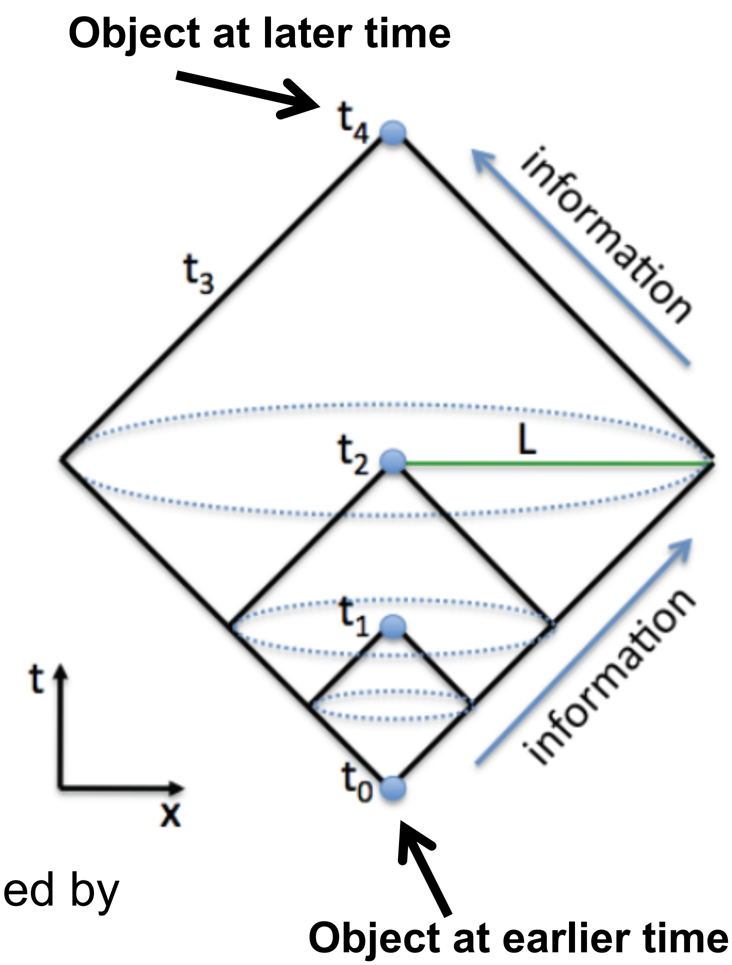
Everything is written on 2D surfaces moving at the speed of light

R. Bousso

The shocking thing is not holography, but rather the **bandwidth limit**….

Bousso: in flat space, information is conveyed by null-spheres expanding and contracting at the speed of light.

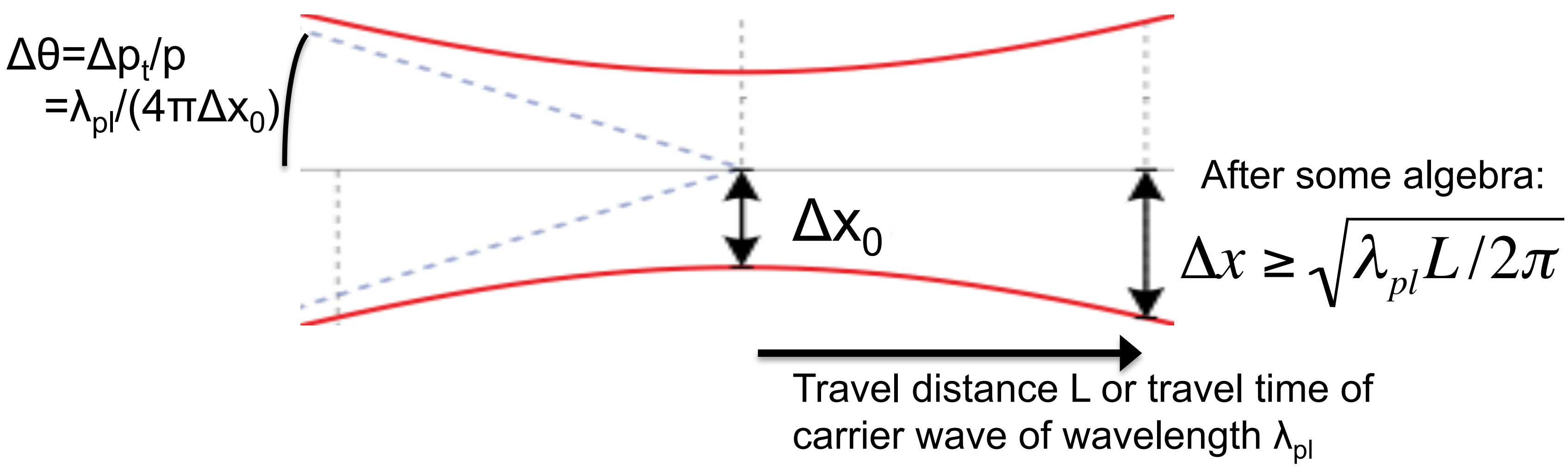




Hogan: Diffraction of transverse position information occurs over the pathlength travelled by this sequence of null spheres as they convey information from one space-time point to another.

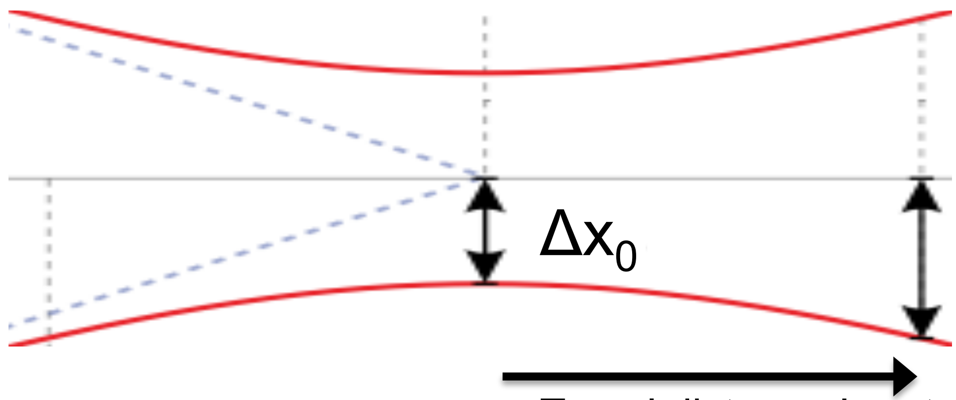
Heisenberg: Beams freely diffract in the absence of non-linear effects

Transverse localization in position causes a transverse momentum spread due to the Heisenberg uncertainty principle.



Suppose that transverse space-time coordinate information is encoded using traveling waves of maximum frequency M_{pl}

- Space-time coordinates must be intrinsically fuzzy due to the Nyquist frequency in the Fourier representation
- The Fuzziness will grow with time due to classical diffraction



After some algebra:

$$\Delta x \geq \sqrt{\lambda_{pl} L / 2\pi}$$

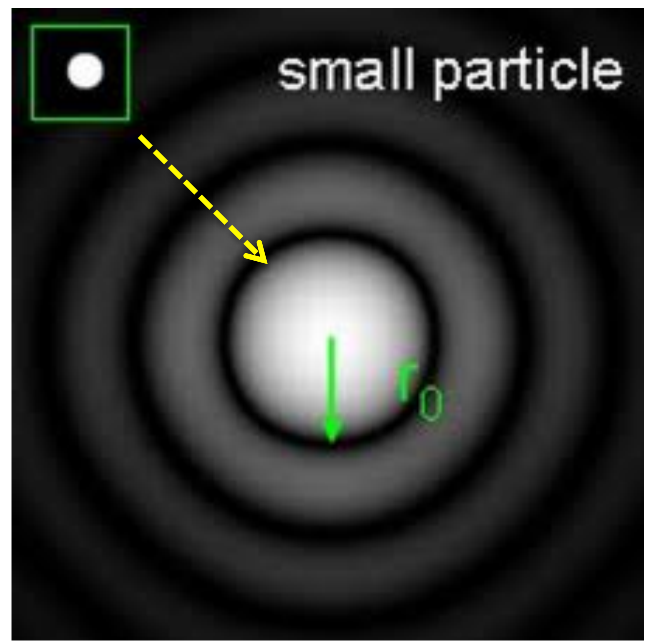
Travel distance L or travel time of carrier wave of wavelength λ_{pl}

Diffraction over a large "lever arm" L can amplify microscopic effects, including Planck scale effects!

Testable hypothesis: Non-linear effects in the propagation of fundamentally encoded information are small

In a hard drive, non-linear magnetic effects preserve the domain size of the magnetic bits, even as the device is being roughly transported.

If non-linear refocusing effects are absent, then fine features grow in size upon propagation of the information.



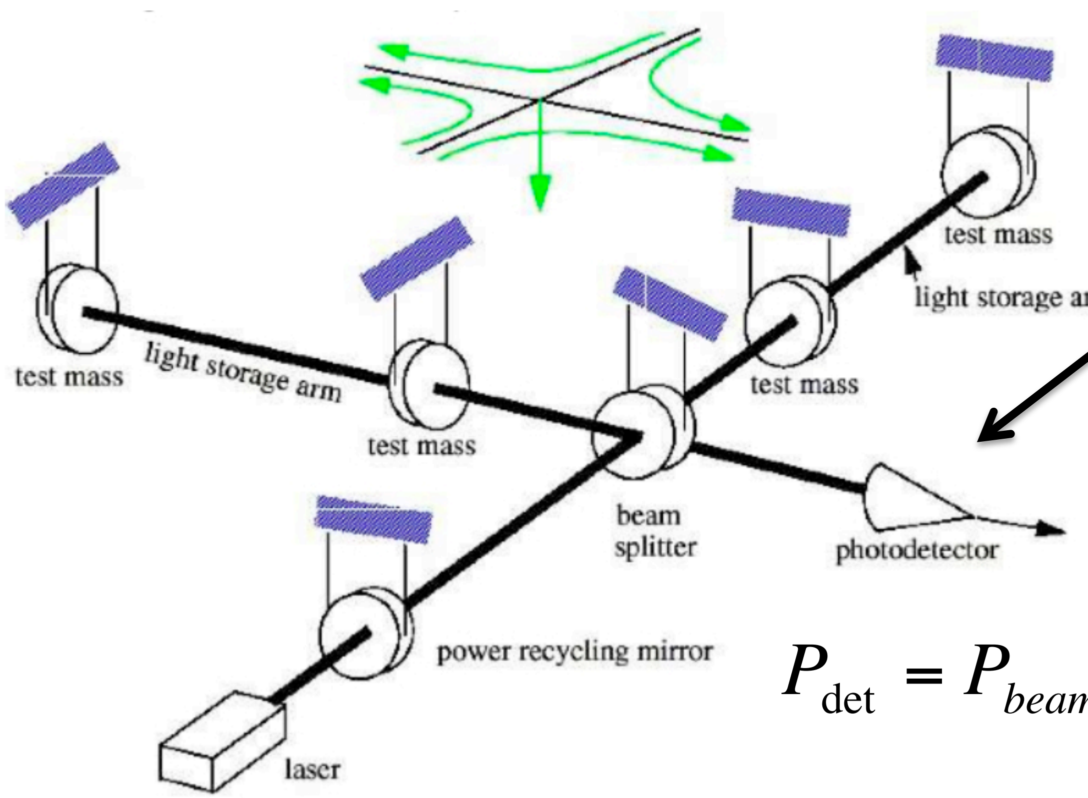
Upon propagation for lab-scale distances L=40m, the blurriness becomes quite large:

$$\Delta x \geq \sqrt{\lambda_{pl} L / 2\pi} = 10^{-17} m$$

Follow your nose!

Experimental Design

A Michelson Interferometer sees motions of its optics



Relative changes in arm lengths are induced by gravitational waves or by **motions of the optics**. The "dark fringe" gets brighter or dimmer in response to the arm path phase difference

$$P_{\det} = P_{beamsplitter} \times \sin^2(\Delta\phi/2)$$

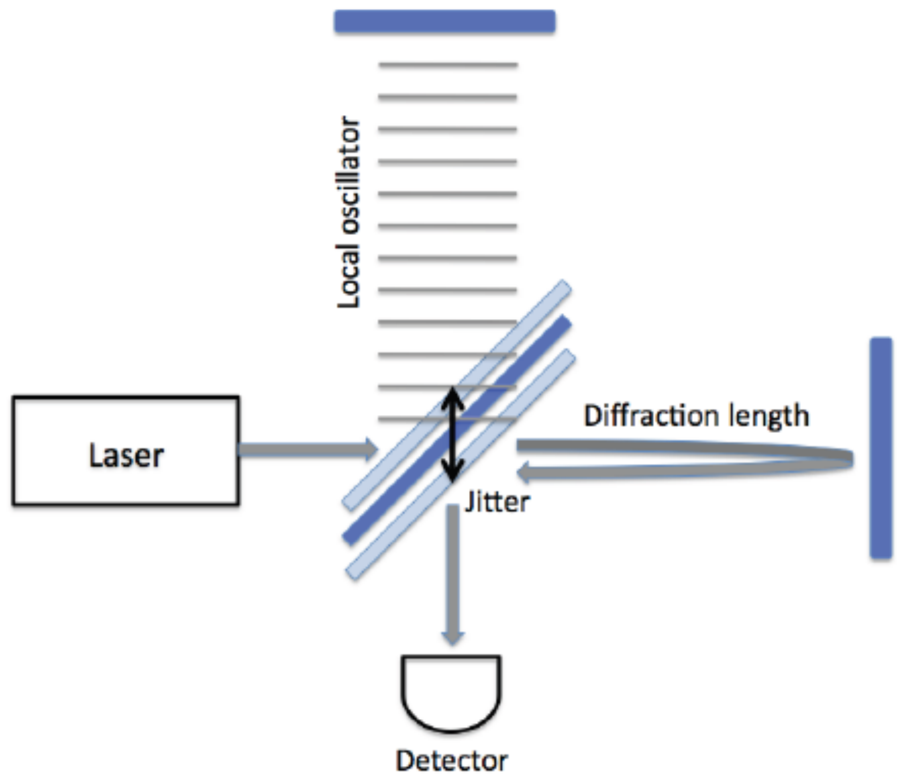
Beamsplitter position noise in a Michelson interferometer

Beam comes in, samples the beamsplitter position, goes down the arms and back.

In this time interval, the **transverse** space-time coordinates *beneath* the beamsplitter have grown uncertain due to the diffractive effect.

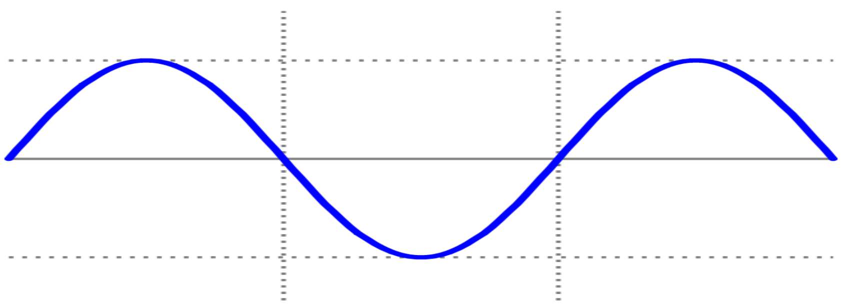
This apparent jitter of the beamsplitter position gives irreducible position noise and hence phase noise in the interferometer.

$$\Delta x = \sqrt{\frac{L \cdot \lambda_{pl}}{2\pi}} = \sqrt{\frac{L}{2\pi M_{pl}}}$$

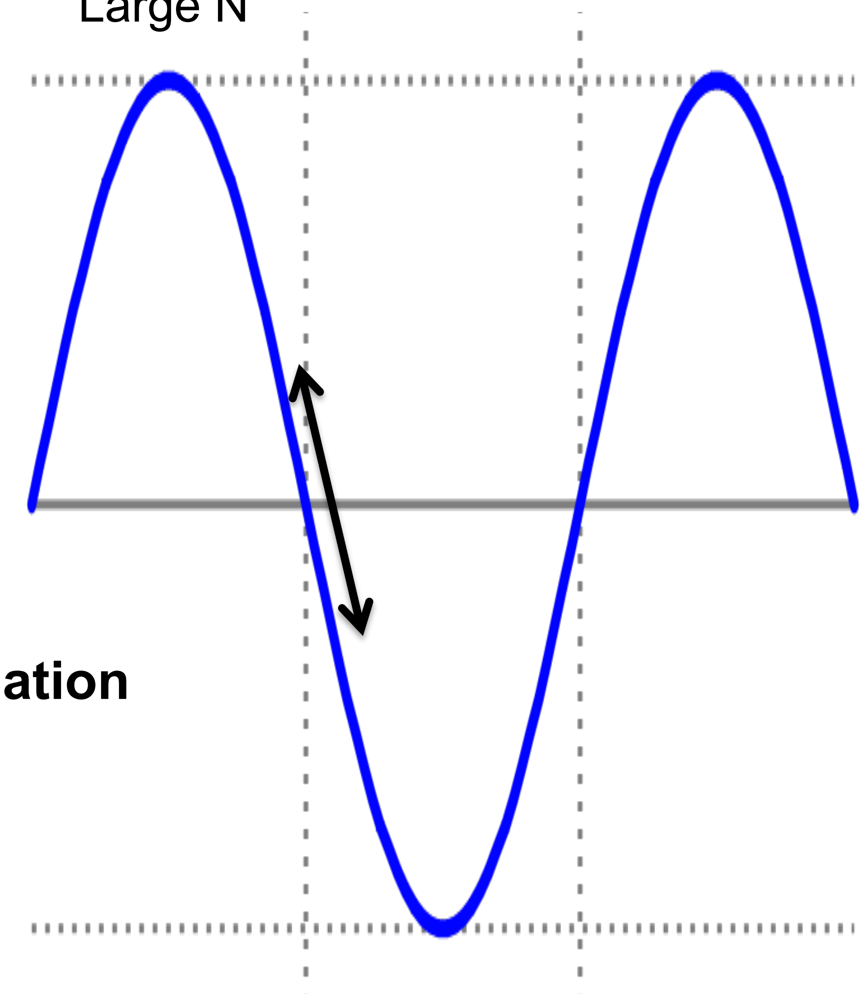


Position resolution depends ***only*** on the photon flux. More photons → sharper fringes

Small N



Large N



Photon number-phase uncertainty relation
$\Delta N \times \Delta\phi = 1/2$

$$\Delta x = \Delta\phi \times \frac{\lambda}{2\pi} = \left(\frac{1}{2\sqrt{N}}\right) \times \frac{\lambda}{2\pi}$$

Contemporary interferometers already have the requisite sensitivity

GEO-600 (Hannover)

Craig Hogan, Beyond Center workshop, January 2010

$\Delta N \times \Delta\phi = 1/2$

Shot noise limited sensitivity:
10 kW → dN/dt = 10^{23} photons/s

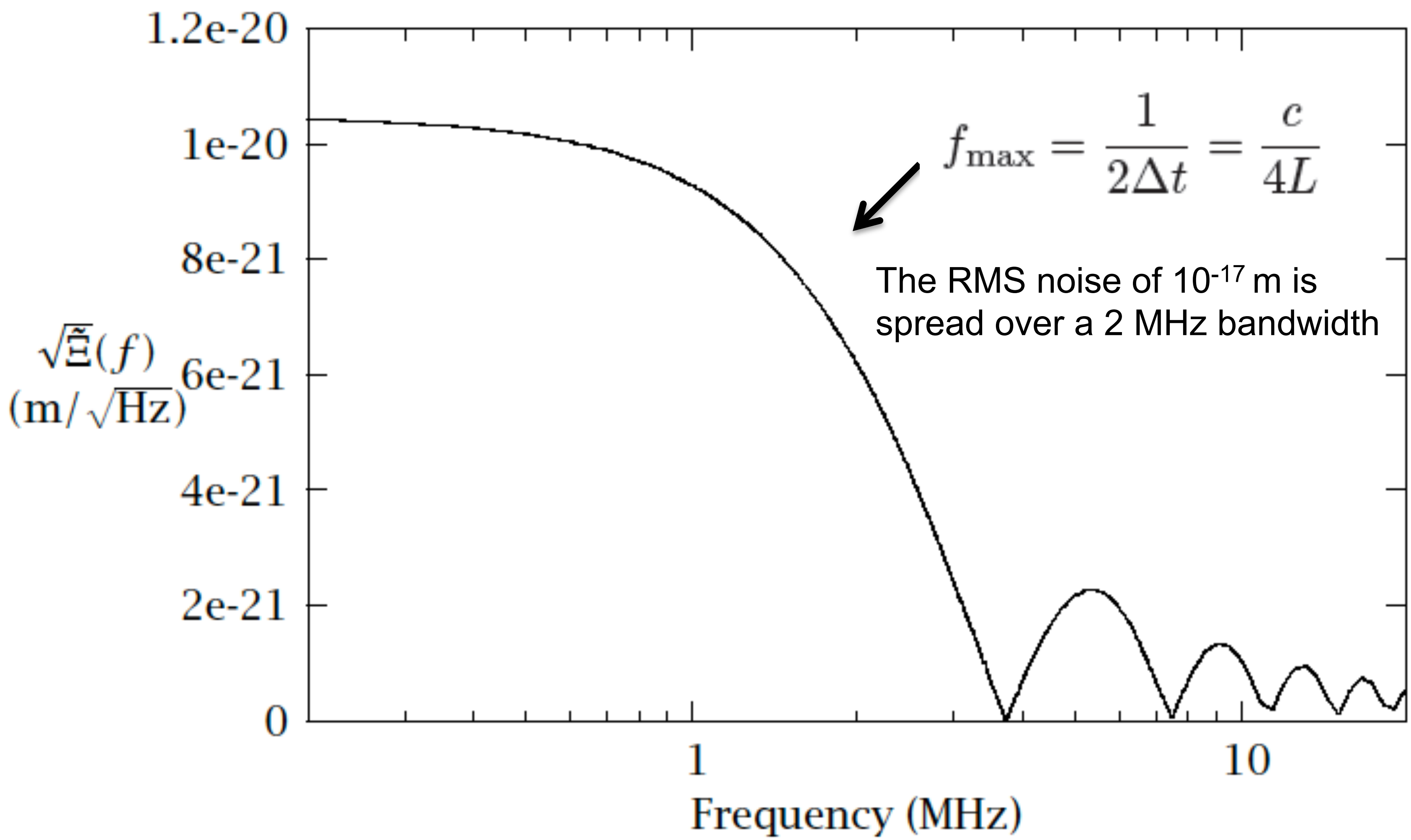
$$PSD_{\Delta\phi} = \sqrt{\frac{2}{dN/dt}} = 4.5 \times 10^{-12} \, rad/\sqrt{Hz}$$

$$PSD_{\Delta x} = PSD_{\Delta\phi} \cdot \frac{\lambda}{2\pi} = 7 \times 10^{-19} \, m/\sqrt{Hz}$$

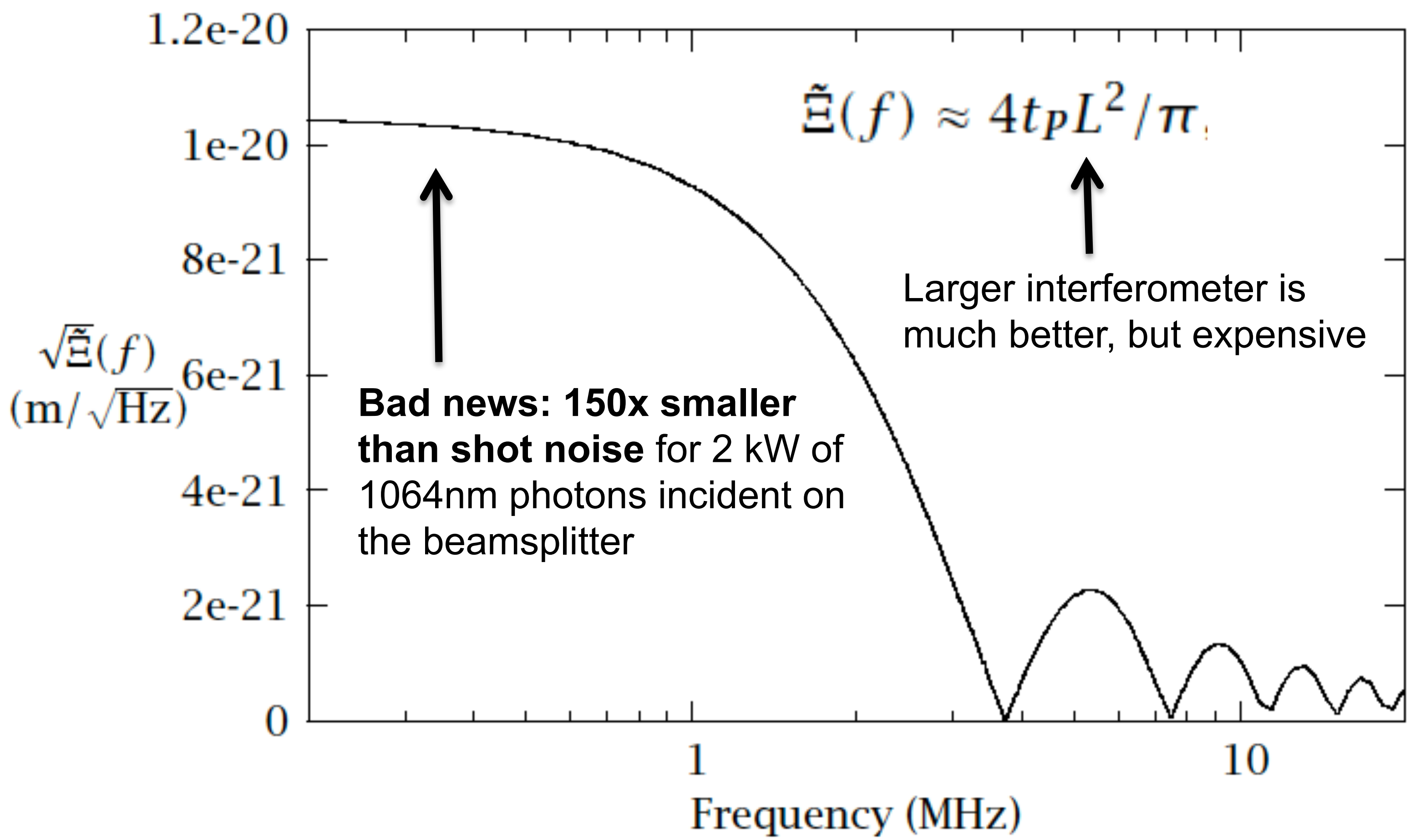
- GEO600 sees mystery noise
- LIGO's photons are stored in arm cavities to measure GW strain
  → **insensitive to transverse motion of optics**.

Predicted position noise power spectrum for a L=40m interferometer

$$\tilde{\Xi}(f) = \frac{(\sigma(2L))^2}{f_{\max}} \geq \left(\frac{\lambda_p L}{\pi}\right)\left(\frac{4L}{c}\right) = \frac{4 t_p L^2}{\pi}$$

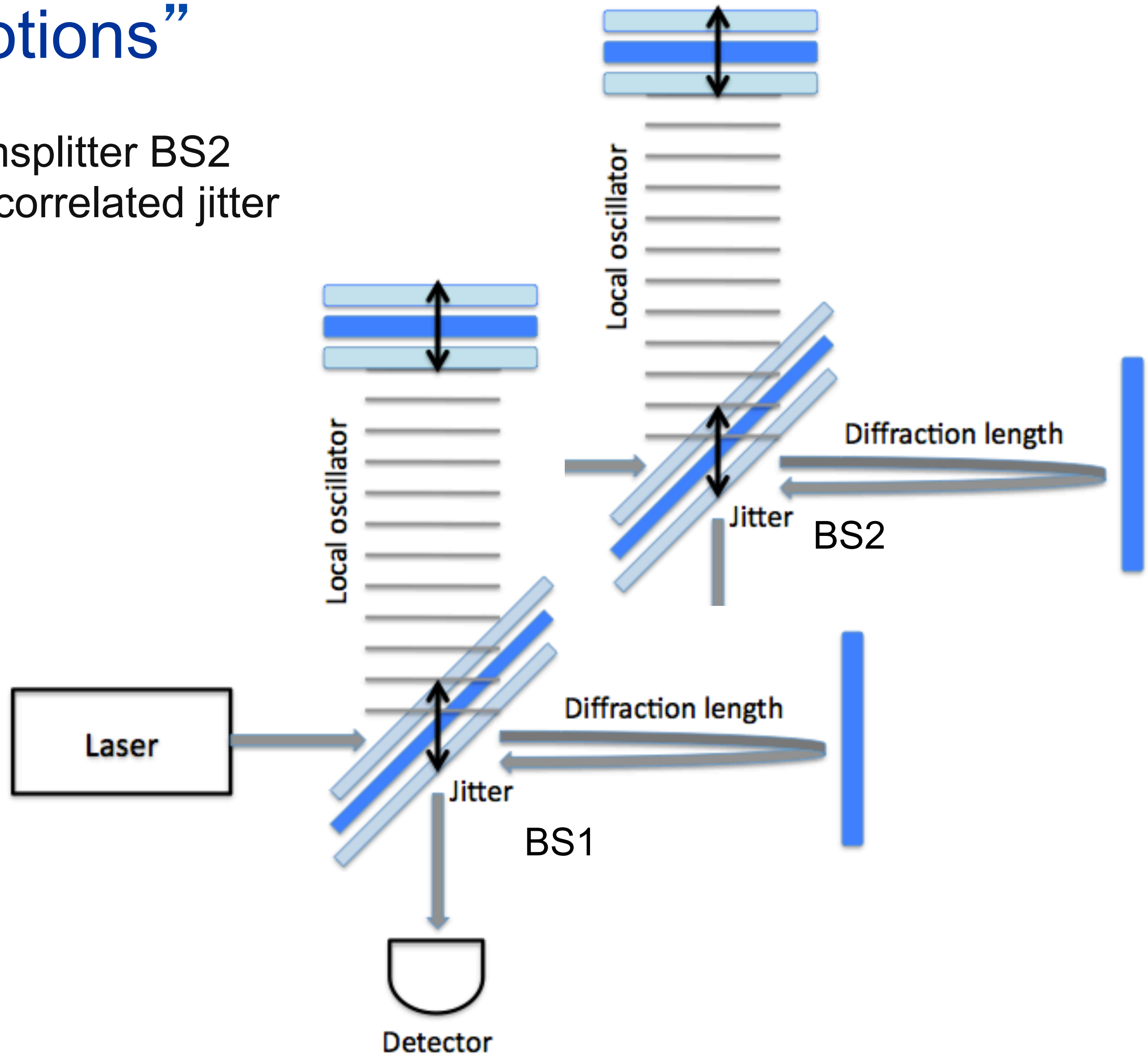


Uh oh, we need a device longer than 40 meters….

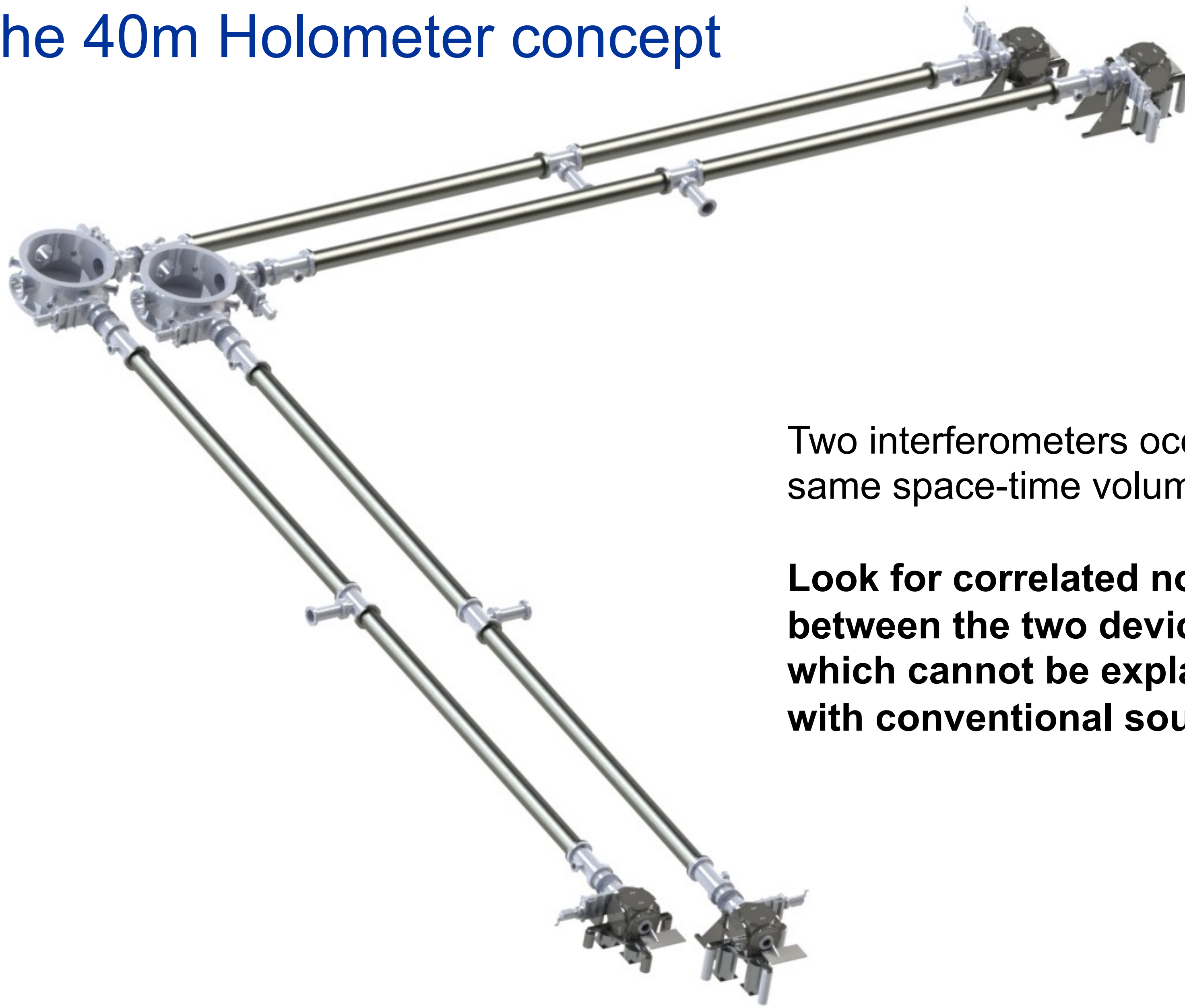


Instead, utilize the prediction of correlated "motions"

- A neighboring beamsplitter BS2 will exhibit partially correlated jitter with BS1.



The 40m Holometer concept



Two interferometers occupy the same space-time volume.

Look for correlated noise between the two devices which cannot be explained with conventional sources.

Strategy: Look for correlated noise in two neighboring Michelson interferometers

- Form the cross-correlation spectrum between noise in the dark fringe detectors for each interferometer
  - The correlated noise signal grows linearly with time
  - Uncorrelated noise product does a random walk and grows as sqrt(time)

$$(\phi_1 X \phi_2)_N = \frac{(\delta\phi_n)^2}{\sqrt{\frac{t_{obs}}{\tau_{sample}}}} + (\delta\phi_{Hogan})^2$$

    - Shot noise, thermal noise, detector noise are all uncorrelated
    - Completely isolate the two devices – separate vacuum, electronics. Only connection is optical data link to perform cross-correlation

  - **Just integrate the cross-correlation for some time until the holographic noise term dominates.**

Estimated integration time

- For signal to noise = 1 in the cross-correlation

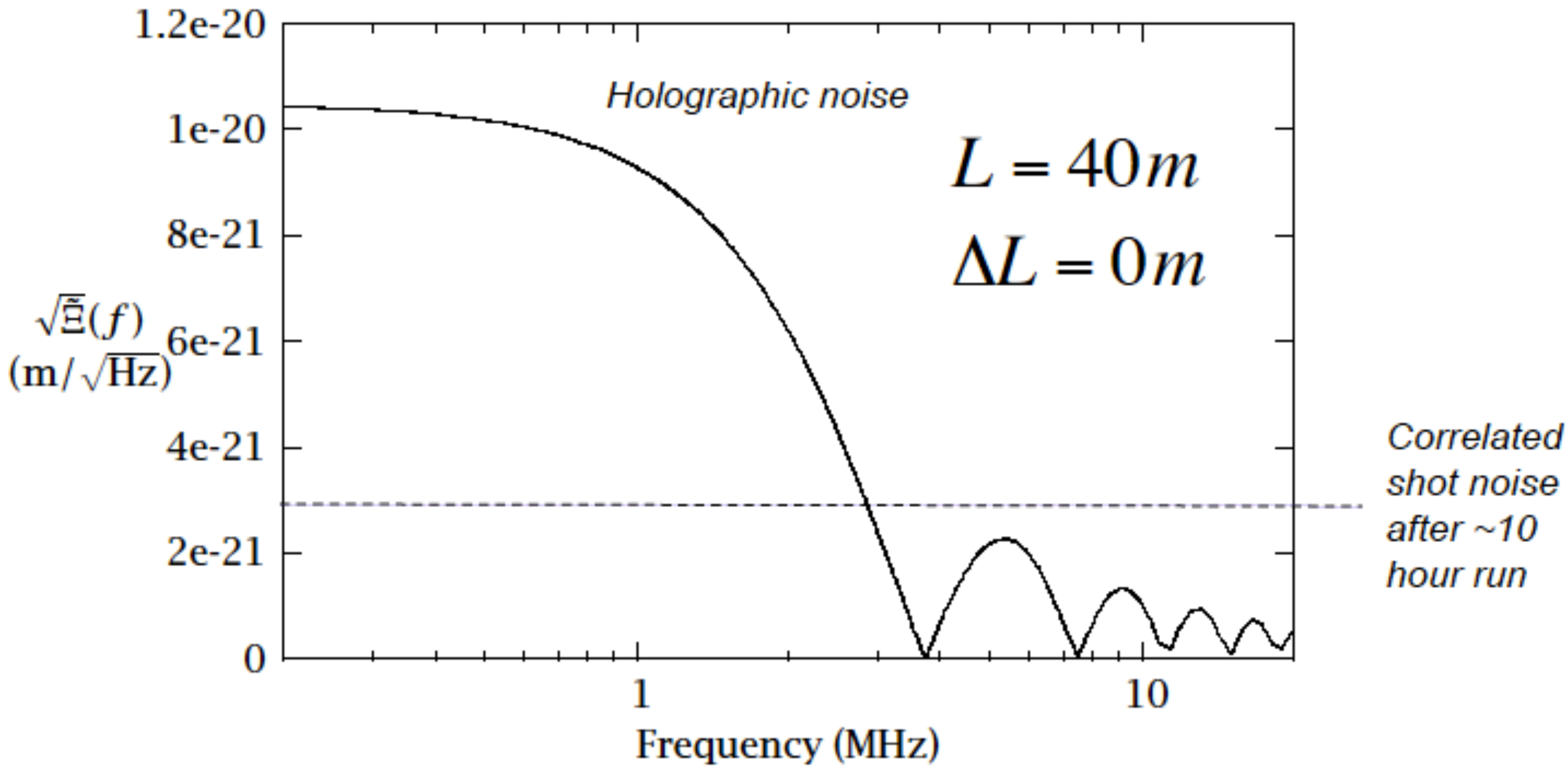
$$t_{obs} > \tau_{sample}\left(\frac{(\delta\phi_n)^2}{(\delta\phi_{Hogan})^2}\right)^2$$

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

- Using P_{BS}=1 kW, λ_{opt} = 1064 nm, L = 40m
  - Shot-noise-limited resolution $\delta\phi_n = 2\times10^{-18}$ m/rtHz
  - Holographic noise $\delta\phi_{Hogan}$ is 150 times smaller

$$t_{obs} > \tau_{sample} \times \left(\frac{(\delta\phi_{noise})^2}{(\delta\phi_{holo})^2}\right)^2 = (270\ ns)^2 \times (150)^4 = 2\ \text{min}$$

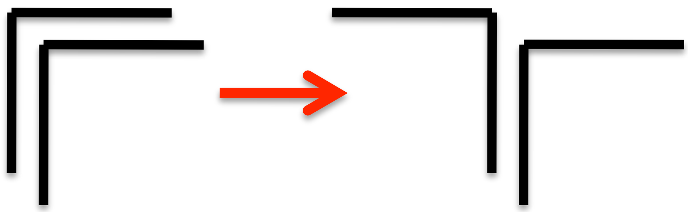
↑ to resolve 2 MHz signal bandwidth


Holographic noise
$L = 40m$
$\Delta L = 0m$
$\sqrt{\tilde{\Xi}}(f)$
$(m/\sqrt{Hz})$
1.2e-20
1e-20
8e-21
6e-21
4e-21
2e-21
0
1
10
Frequency (MHz)
Correlated shot noise after ~10 hour run

Distinguishing exotic noise from conventional noise

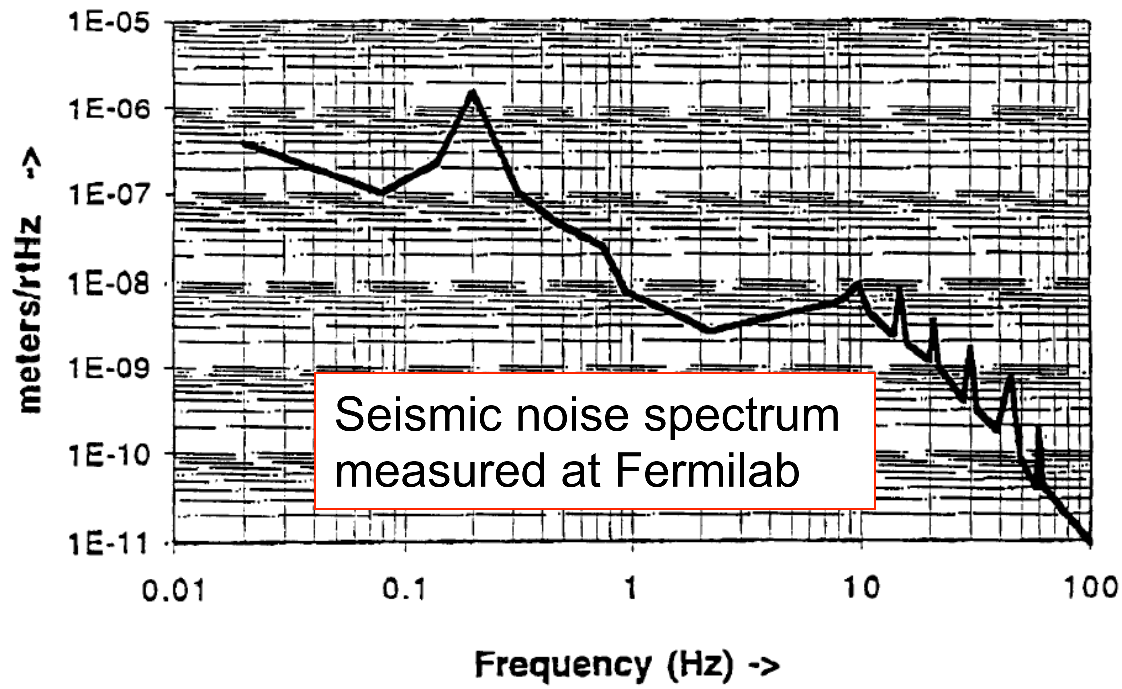
- The holographic noise has a predicted spectral shape
  - Normalization of spectrum scales as arm length L^2
  - Interferometer response function cuts off at f=c/2L
  - Conventional RF backgrounds are usually frequency dependent (narrow lines, ~1/f, etc.)

- Experimental knobs:



  - ➢Orientation of two interferometers
    - ➢ Nested for maximum correlation
    - ➢ Back-to-back to turn off correlation (information then travels along independent paths)
  - ➢Change arm length to verify scaling with L.

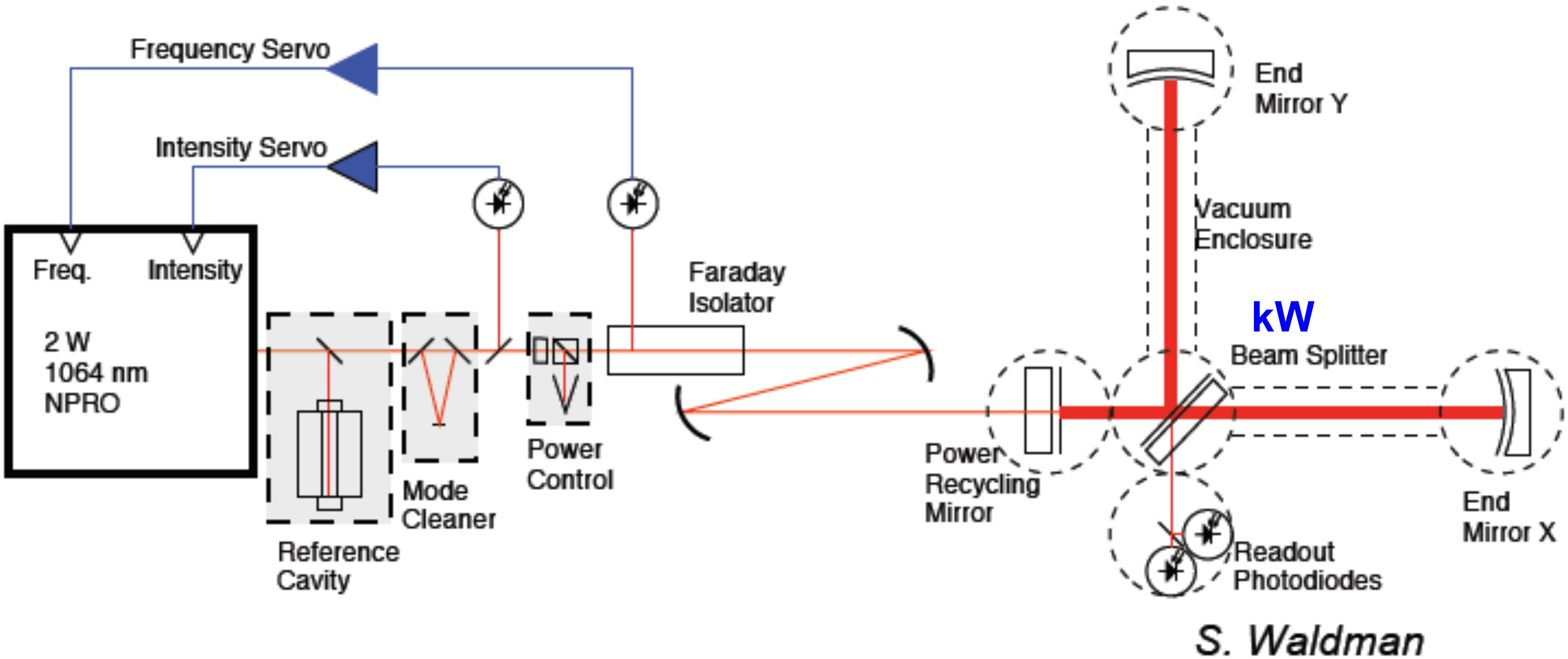
Simplifications relative to GW detectors



- The exotic noise measurement can be made at high frequencies where seismic noise is negligible
  - The holographic noise is predicted to be white for f<c/4L ~ few MHz
  - Most of the noise problems (and corresponding experimental effort) in gravity wave experiments are at lower frequencies

Holometer optical configuration

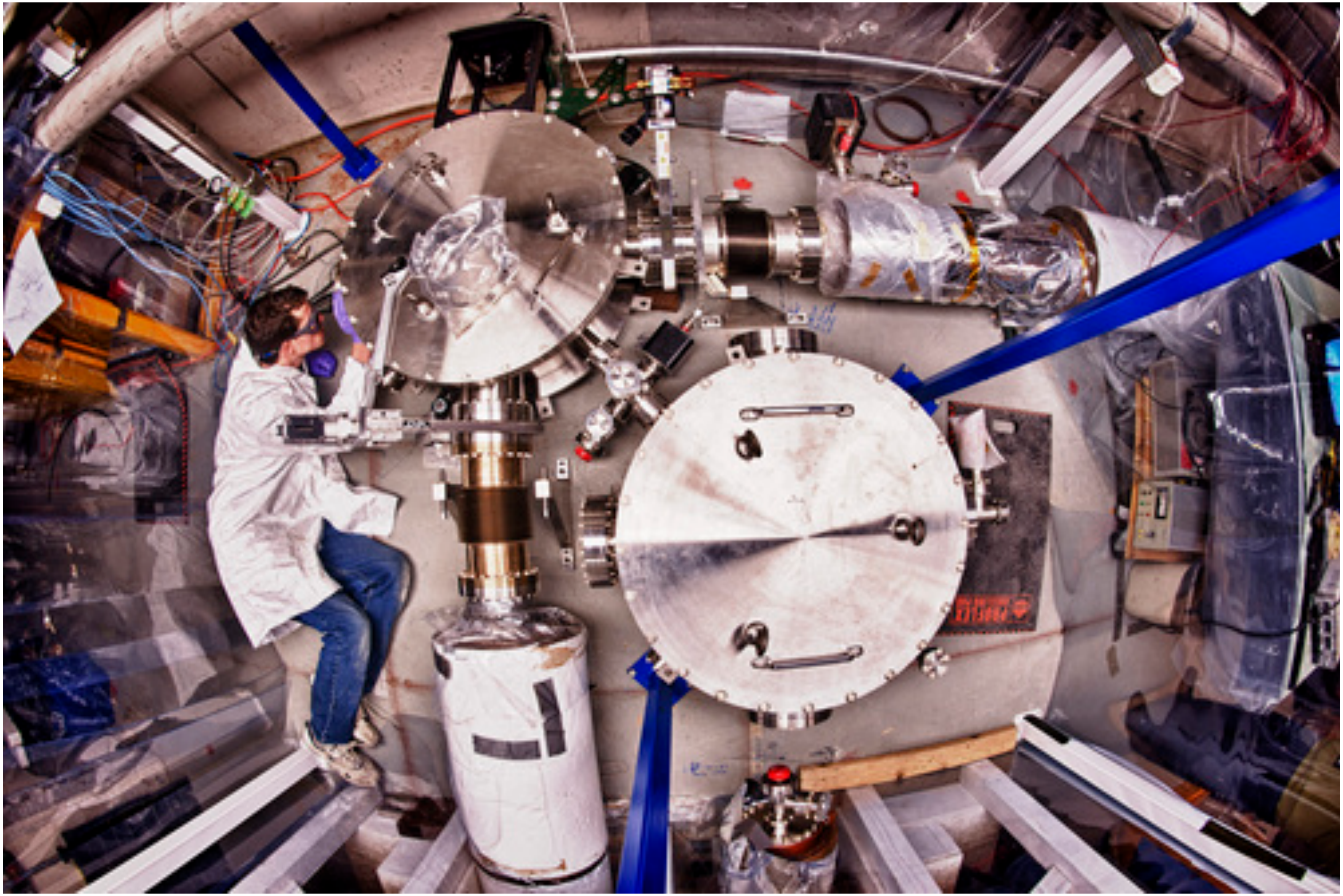
(We need 2 of these)



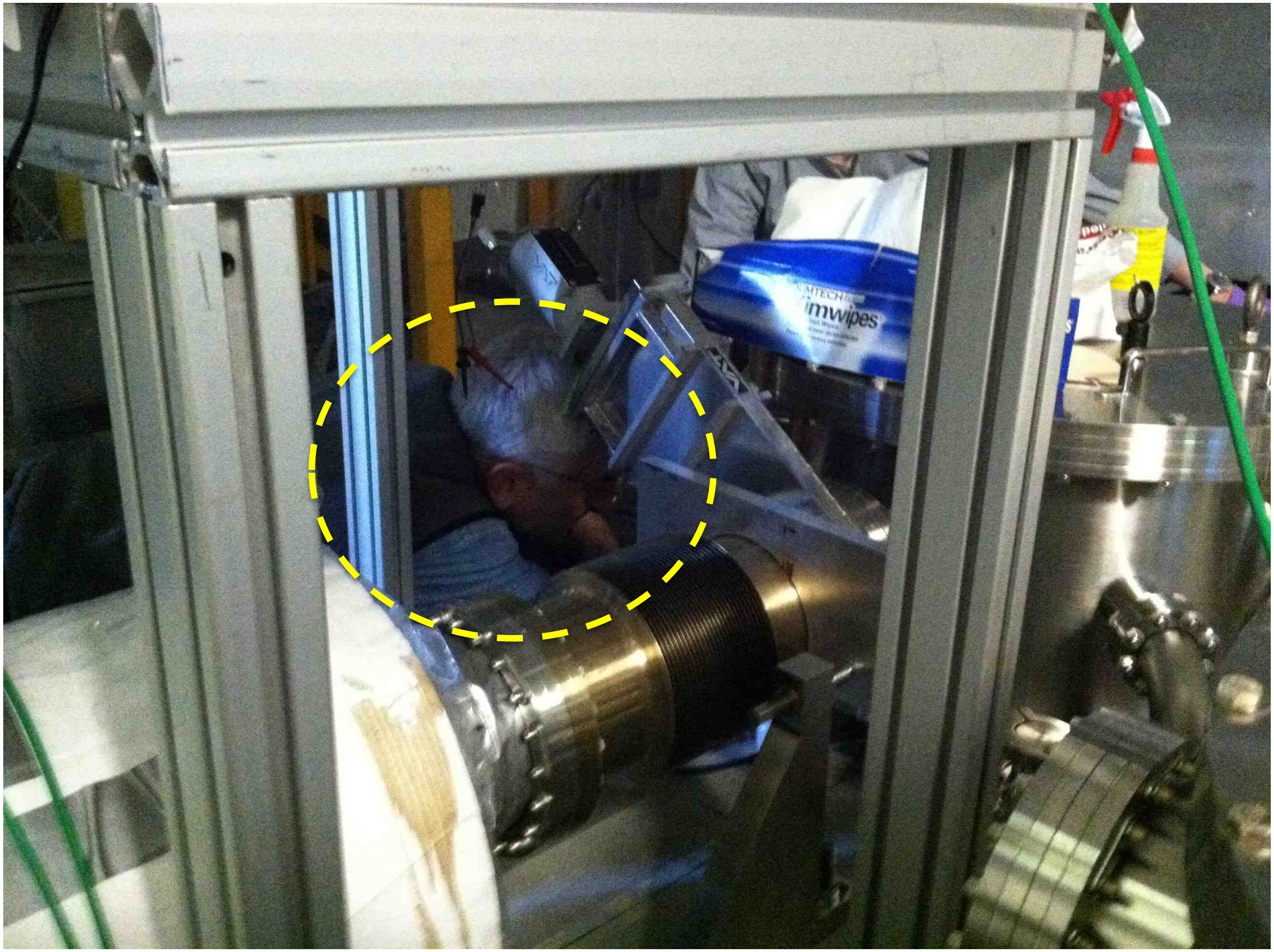
Fabry-Perot cavity gives power recycling factor of 1000 → kW beam

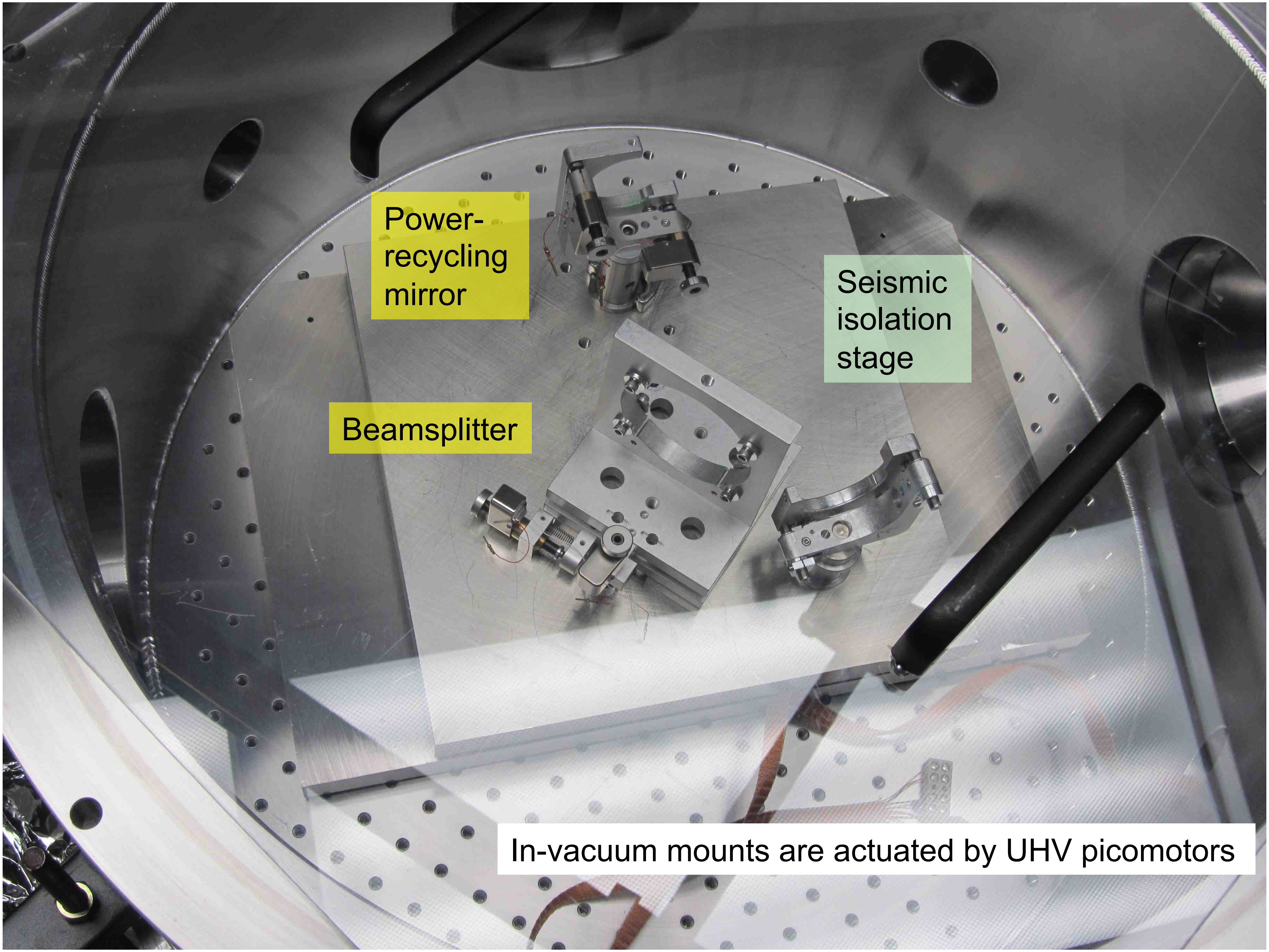
The Holometer is located at MP8, a beamline in the meson area of FNAL

UHV vacuum is needed to keep optics clean



Holometer provides hardware training opportunity for students (and theorists)




Power-
recycling
mirror
Seismic
isolation
stage
Beamsplitter
In-vacuum mounts are actuated by UHV picomotors

Pipes are insulated with 4" fiberglass + intermediate and exterior radiation shield

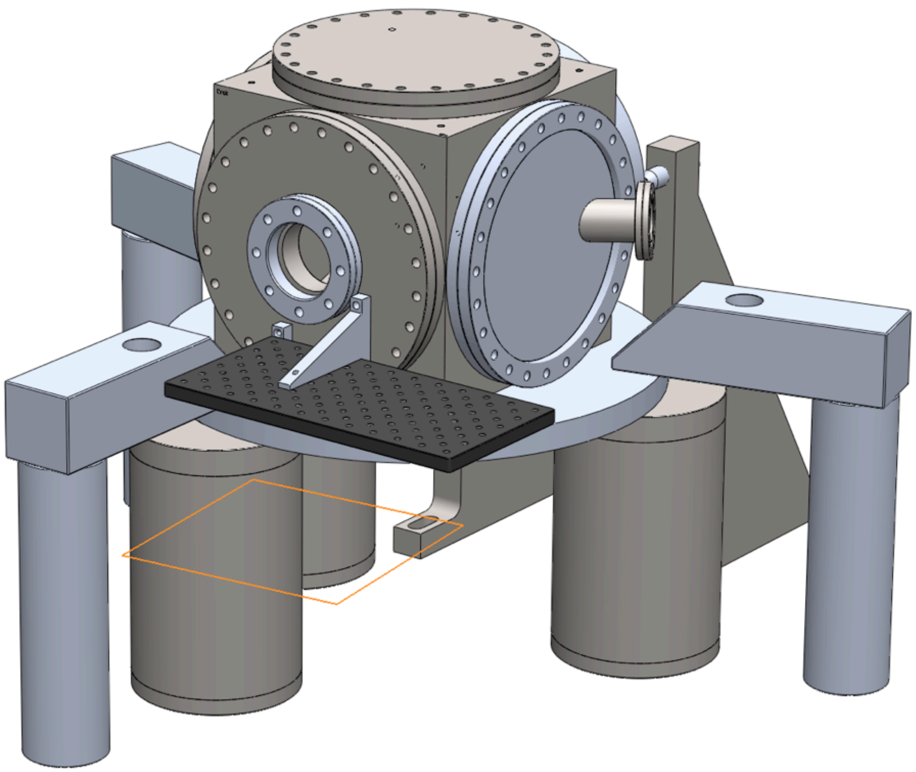
Bake in situ to 200C by flowing 200A current through stainless steel vacuum pipe

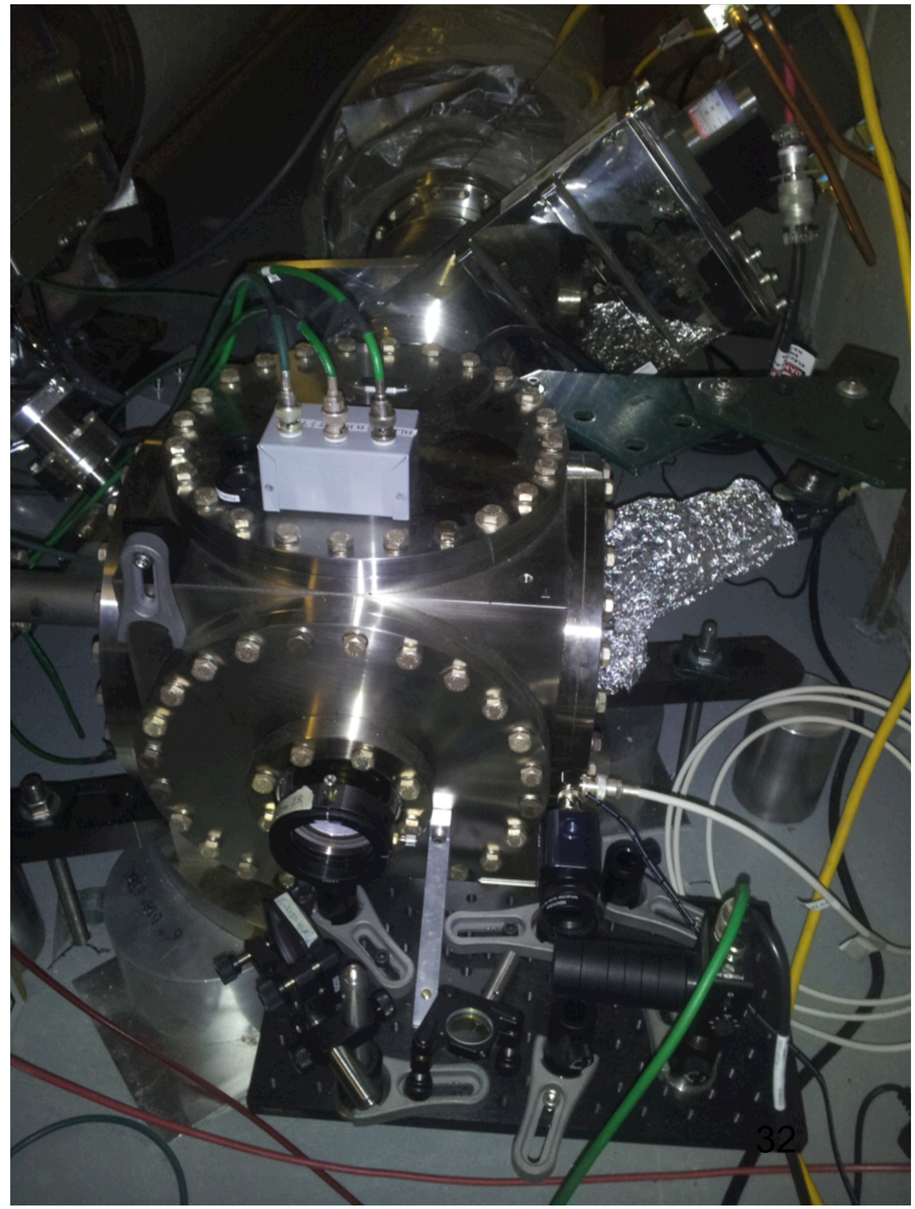
Climate controlled endstation enclosure

Concrete floor referenced to earth 5' underground to obtain effective thermal expansion coefficient of 10^{-10}/K over the 40m arm distance.

Clean room for access to end mirrors

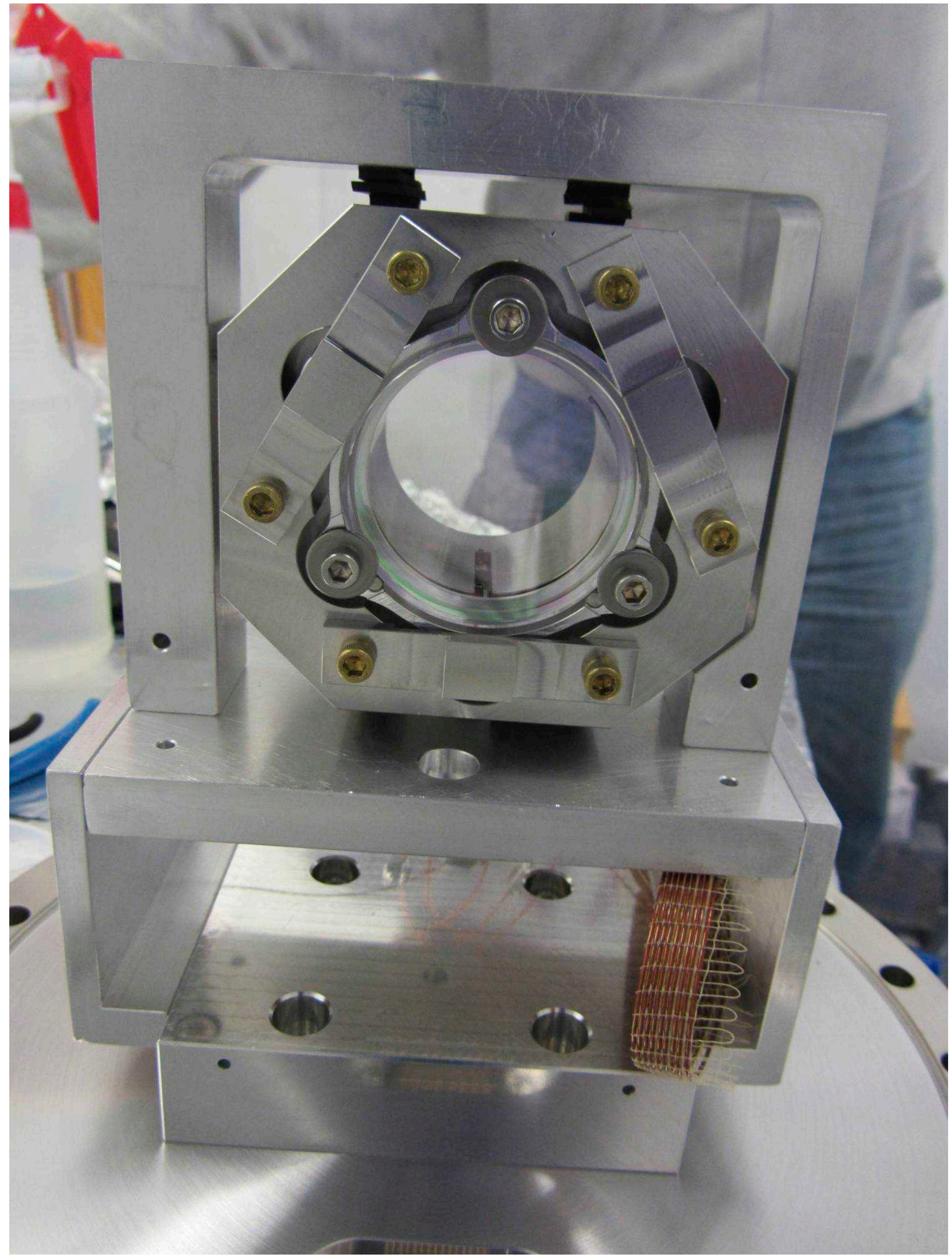
End mirrors can be adjusted by externally moving the vacuum endstation





Endstation vacuum mirror mount

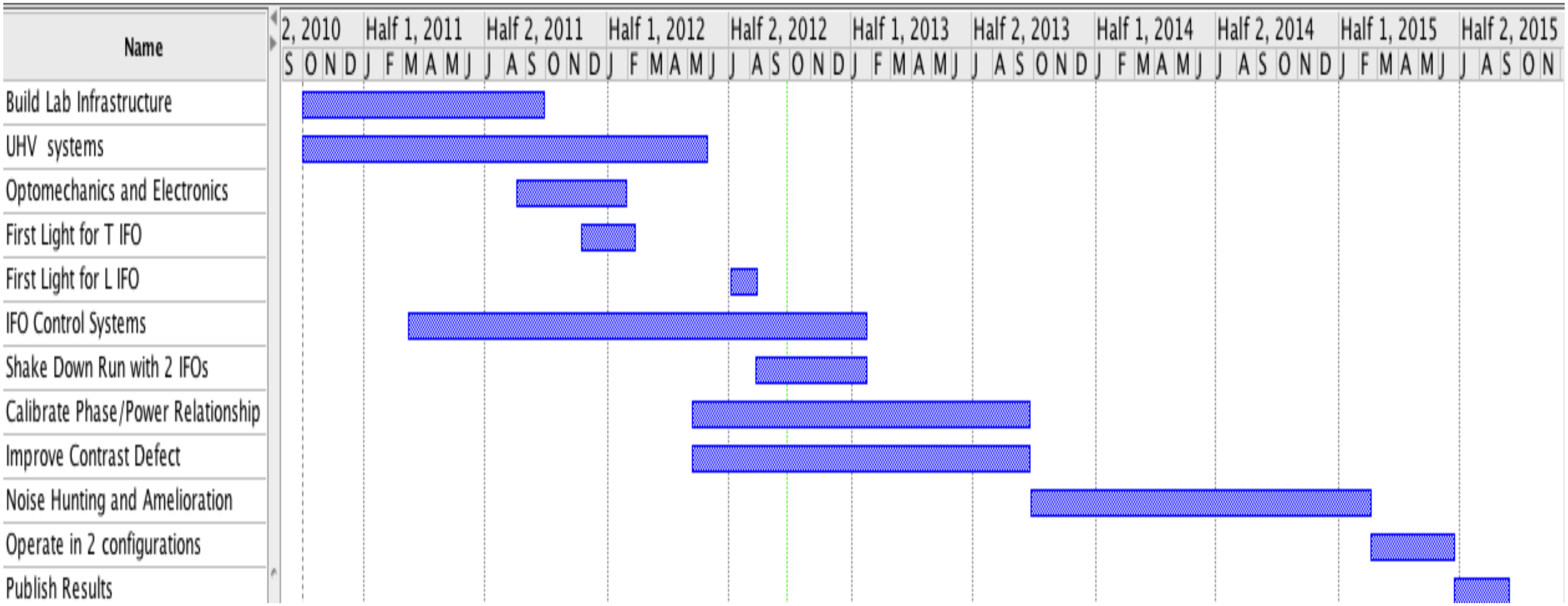
- Actuated by 3 spring-loaded PZT stacks.
- North and East end mirrors are driven in antisymmetric motion to compensate for **low frequency** seismic noise to maintain a stable operating point.
- Search for high frequency perturbations about this operating point



2/2012: First interferometer on-line.
9/2012: Second interferometer on-line

Best performance: Power-recycled lock at 300W cavity power.
Stable for ~1 hour.

Schedule


Name
2, 2010
Half 1, 2011
Half 2, 2011
Half 1, 2012
Half 2, 2012
Half 1, 2013
Half 2, 2013
Half 1, 2014
Half 2, 2014
Half 1, 2015
Half 2, 2015
S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N
Build Lab Infrastructure
UHV systems
Optomechanics and Electronics
First Light for T IFO
First Light for L IFO
IFO Control Systems
Shake Down Run with 2 IFOs
Calibrate Phase/Power Relationship
Improve Contrast Defect
Noise Hunting and Amelioration
Operate in 2 configurations
Publish Results

Summary

- The goal is to probe the quantum structure of space-time itself, using well-developed interferometer techniques.

- Studies of space-time are part of the DOE OHEP mission

- The question being asked is independent of specific theoretical models:
  - Is fundamental encoding of space-time information linear or non-linear?
  - If linear, then by order-of-magnitude estimates, Planckian effects are accessible to experiments
  - **Follow your nose**

- **A successful detection of exotic effects by 2015 would motivate future probes of the Planck scale.**