The Holometer:

A Measurement of Planck Scale Quantum Geometry

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The Planck Scale

Max Planck came up with his constant, *h*, to give discrete energy steps to EM radiation. This way he could avoid the "ultra-violet catastrophe" and match the observed blackbody spectrum.

He did not take the consequences of quantization too seriously but he recognized that, along with G, his constant provided a set of universal units for physics.

$$l_P \equiv \sqrt{\hbar G_N / c^3} \sim 10^{-35}\,\mathrm{m}$$

$$t_P = c\,l_P = 5 \times 10^{-44}\,\mathrm{seconds}$$

A "granularity" too small to observe directly

The meaning of the length was not known

And it still isn't

We do know that at this scale something has to work differently

To confined a particle to a scale ~ λ requires an energy

$$E = \hbar c / \lambda$$

an object of this energy has a black hole radius of

$$R = \frac{2GE}{c^4}$$

Setting $R = \lambda = l_P$ gives a length scale of

$$m_P = 10^{19}\,\mathrm{GeV}/c^2 = 22\,\mu g$$

$$l_P = \sqrt{\frac{2G\hbar}{c^3}}$$

Any particle confined to this size is a black hole.

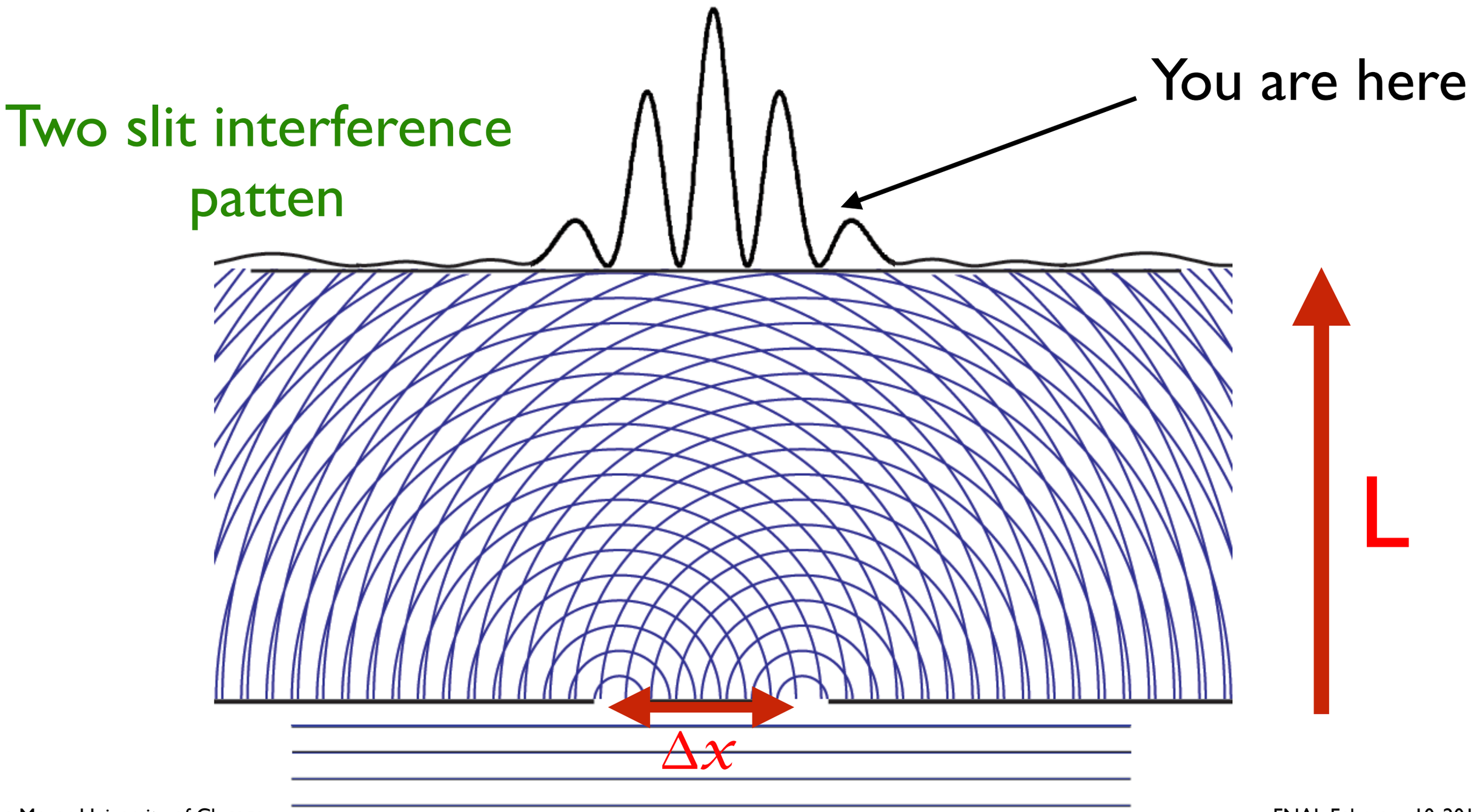
Suppose we assume that the Planck length is a smallest possible distance

No signals could be sent with wavelength less than the Planck length or frequency higher than $1/t_P$.

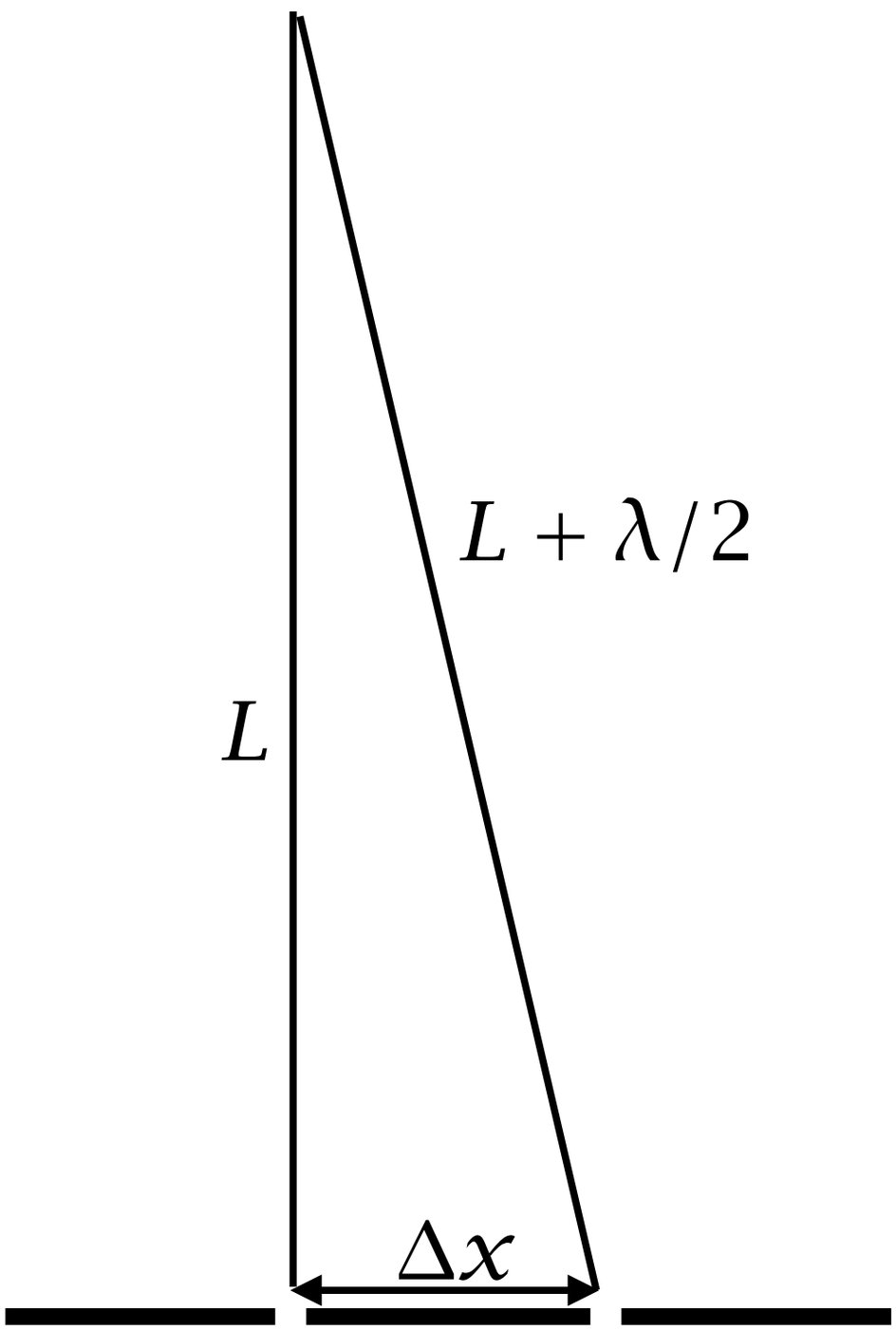
What would be the consequences?

Thought experiment: measure the distance between two closely spaced slits some distance away.

Find the separation between two slits a distance L from you. At your position his would be done by measuring the interference pattern



Using the information available at the distance *L*:



Condition for the first null in the interference pattern

$$
\begin{aligned}
(\Delta x)^2 + L^2 &= (L + \lambda/2)^2 \\
\Delta x &= \sqrt{L\lambda} \qquad \lambda \ll L
\end{aligned}
$$

The shorter the wavelength, the smaller we can measure a small slit spacing.

If we set $\lambda = l_P$ then there is a minimum slit separation we can measure *in principle*.

Assuming that there is a shortest time or smallest length has the consequence of a limit on resolution for distant objects.

That limit can be much bigger than the Planck length, namely $\Delta x_{\perp} = \sqrt{L l_P}$.

The consequences of this limit have not been tested by any experiment.

So far, its only a thought experiment.

Black Hole Entropy

Black holes are thought to emit Hawking radiation. This couples them thermodynamically to the outside world.

Bekenstein used a thermodynamic argument to show that the Black Hole entropy was proportional to its area.

The constant of proportionality was shown to involve the Planck Length

$$S_{BH} = \frac{A}{4l_P^2}$$

A is the surface area of the black Hole

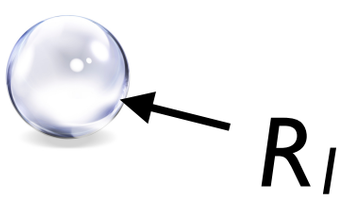
How about flat space-time?

It can be also be shown that systems of matter and black holes in any combination must also have their total entropy be bounded by an enclosing surface.

This is the holographic principle.

Suppose we take this seriously

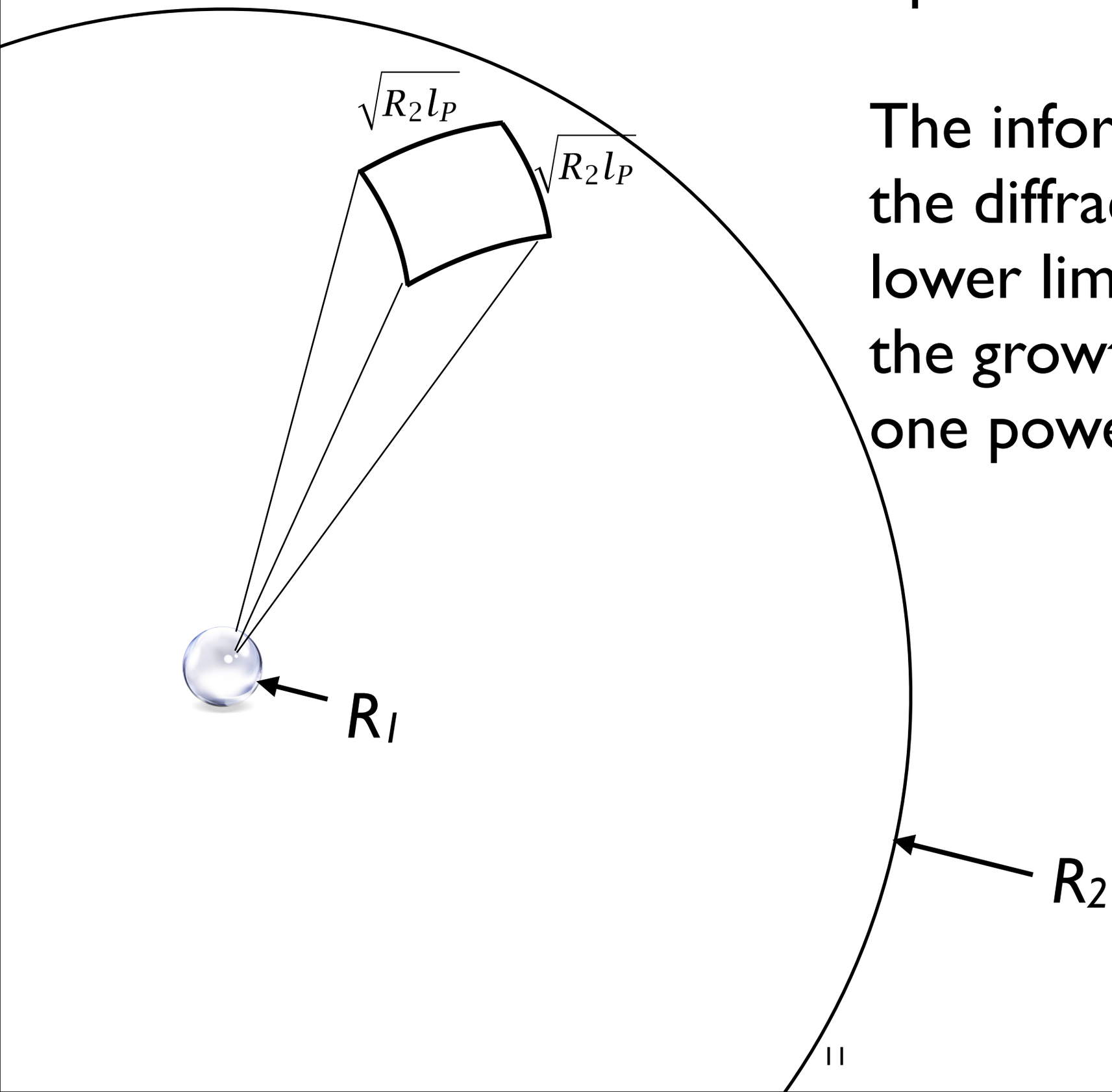
Take a system with radius R_1 and a total number of states set by S_1 and expand it to a new size, R_2.



The holographic principle has the information content growing as R^2 but 'normally' we would think it would grow as R^3.

R_2

Its interesting that the limit of information at a distance helps here



The information lost due to the diffractive effect of a lower limit to length reduces the growth of information by one power of *R*.

The diffraction due to the Planck length limit expands the scale of the effect.

The transverse uncertainty within a large laboratory instrument, like 40 meters, is

$$\left\langle x_{\perp}^{2} \right\rangle^{1/2} = 1 \times 10^{-17}\,\mathrm{m}_{\mathrm{RMS}}$$

It is a measurable distance!

Michelson Interferometers have very high sensitivity to beamsplitter position, independent of arm length.

The Holometer Group

Fermilab

- A. Chou (co-PI, Project Manager)
- H. Glass
- C. Hogan
- C. Stoughton
- R. Tomlin
- W. Wester

U Chicago

- B. Lanza
- L. McCuller
- S. Meyer (co-PI)
- J. Richardson

MIT

- M. Evans
- R. Weiss

U Michigan

- D. Gustafson

Northwestern

- J. Steffen

Vanderbilt

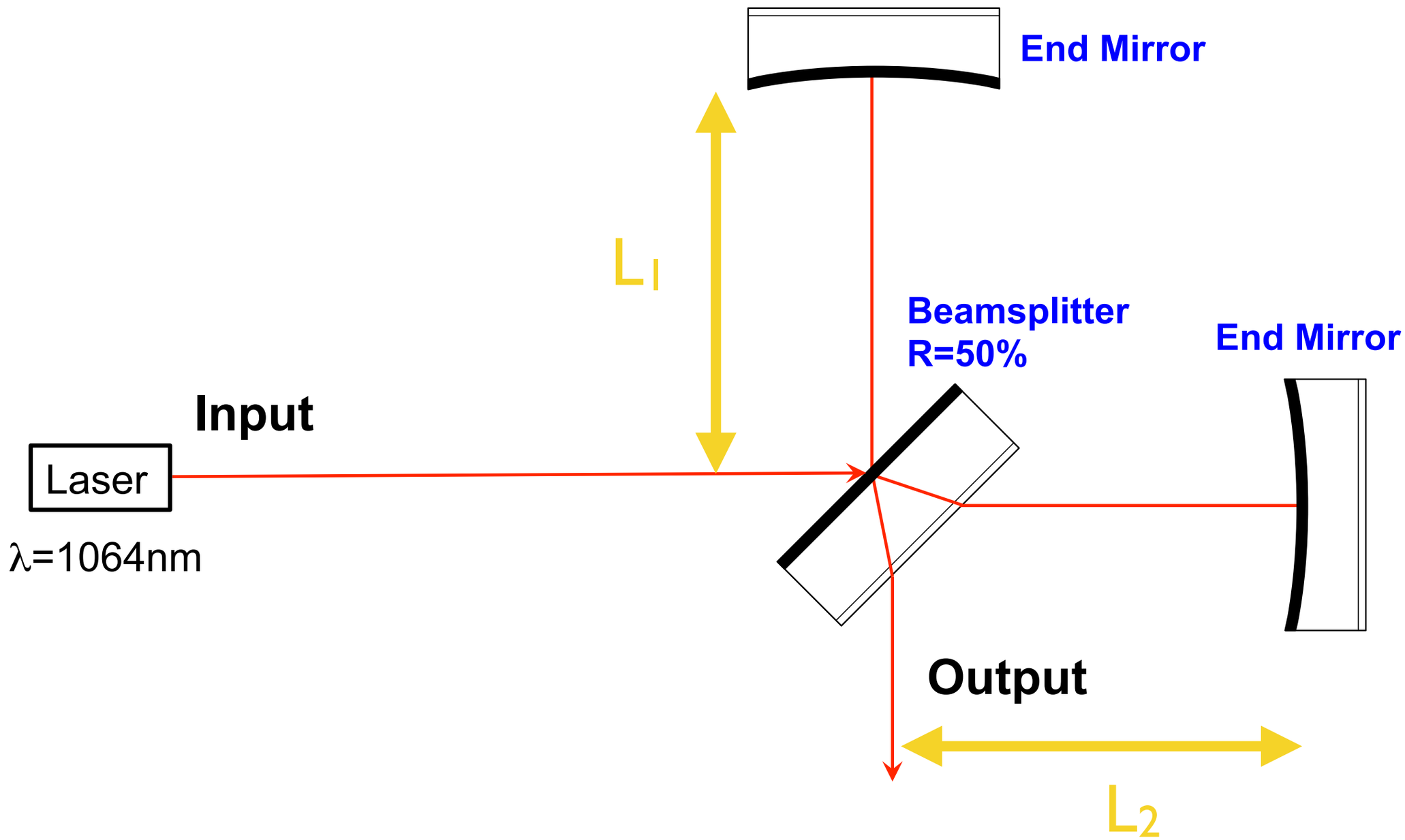
- B. Kamai

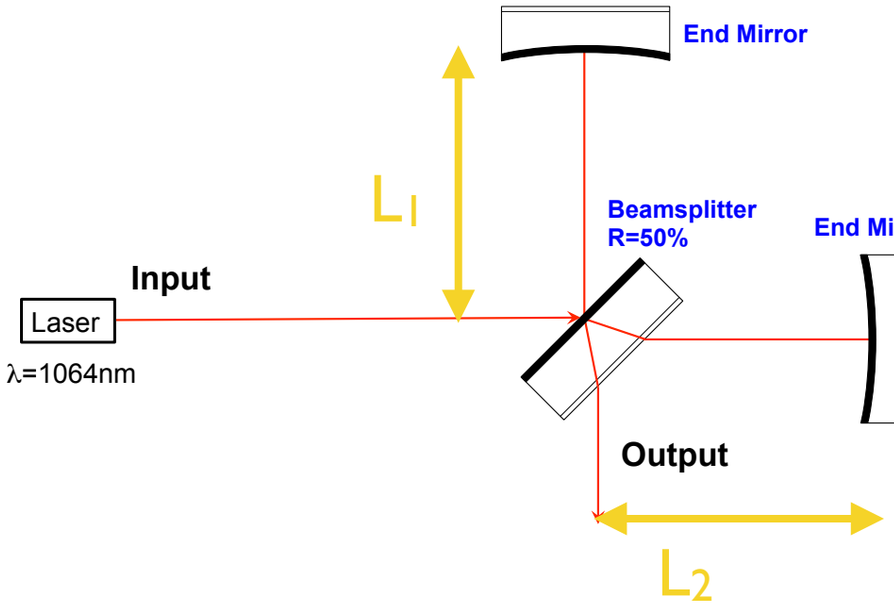
SpaceX

- S. Waldman

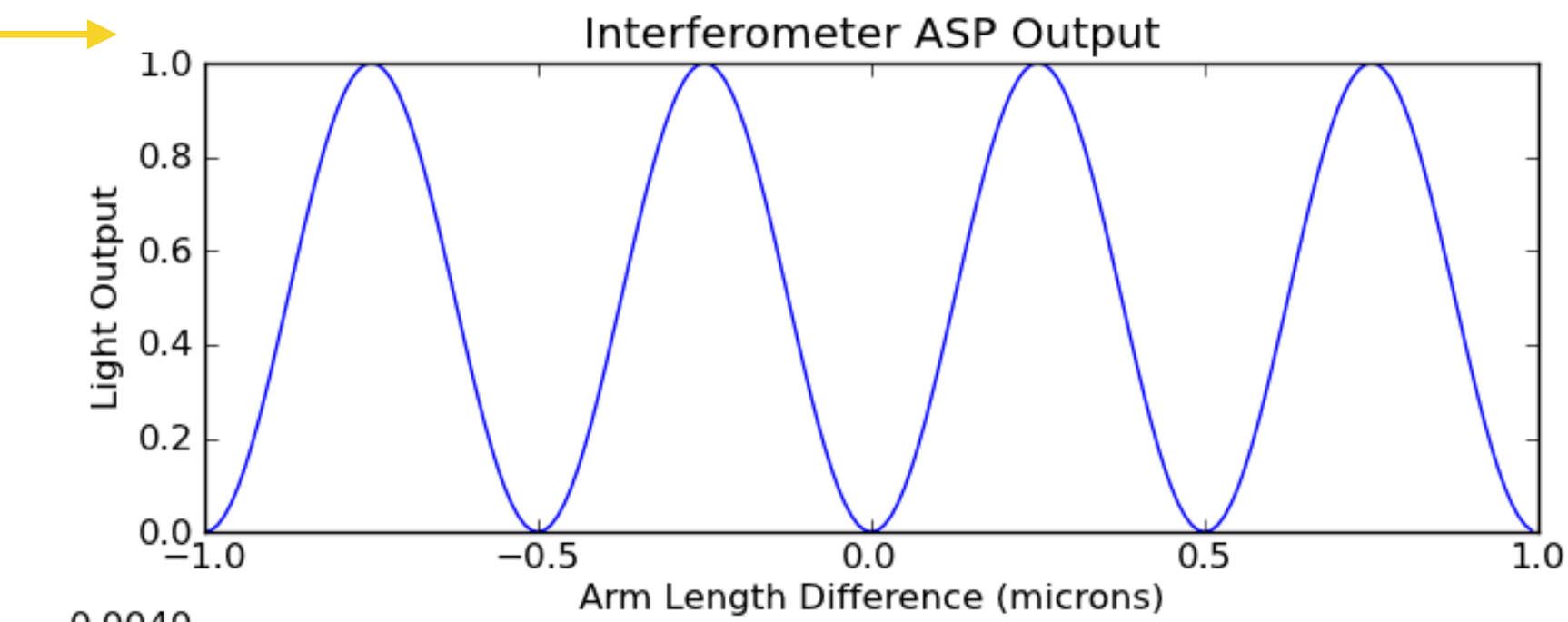
4 Ph.D students, many undergraduate researchers (including 3 senior thesis projects), REU program students, high school students.

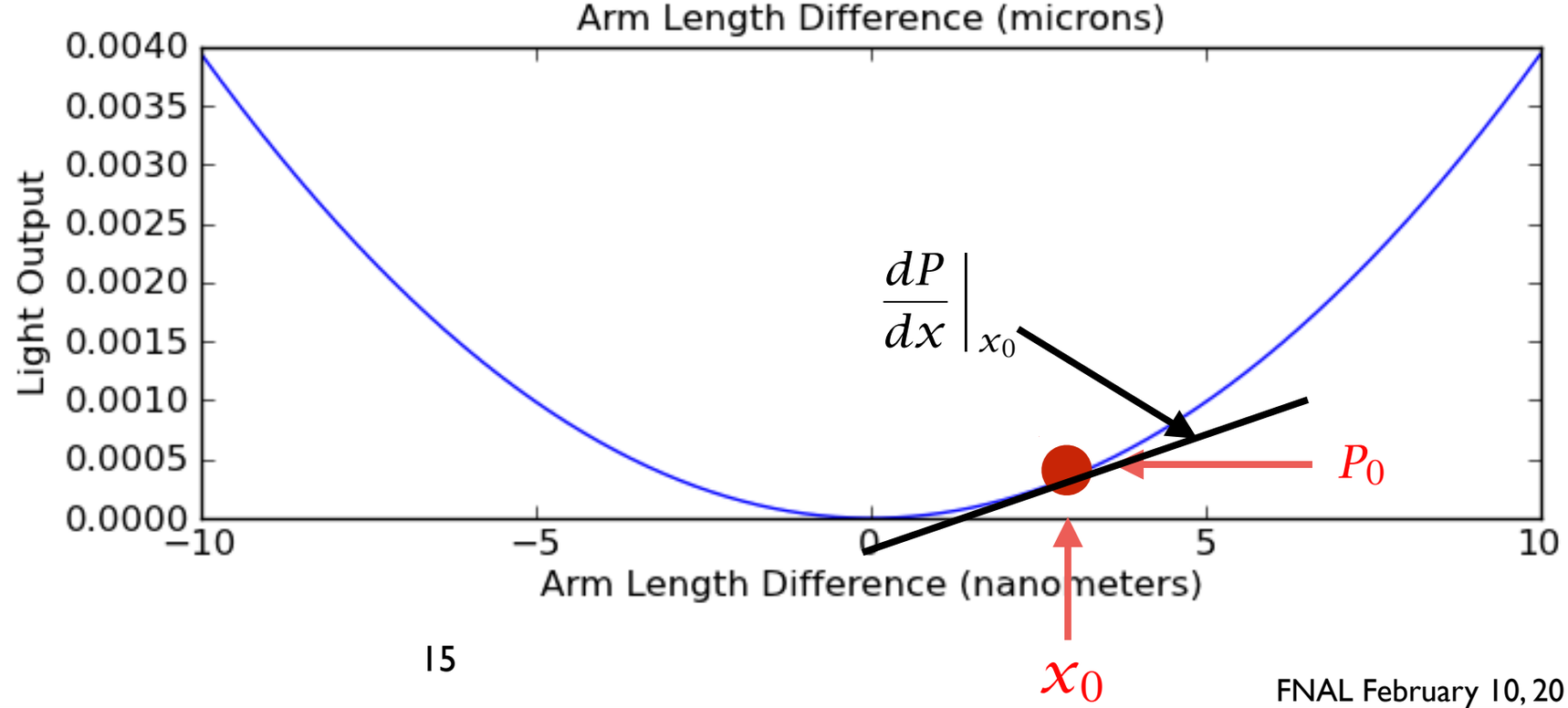
Schematic of a Michelson Interferometer




End Mirror
L_1
Beamsplitter
R=50%
End Mirror
Input
Laser
λ=1064nm
Output
L_2

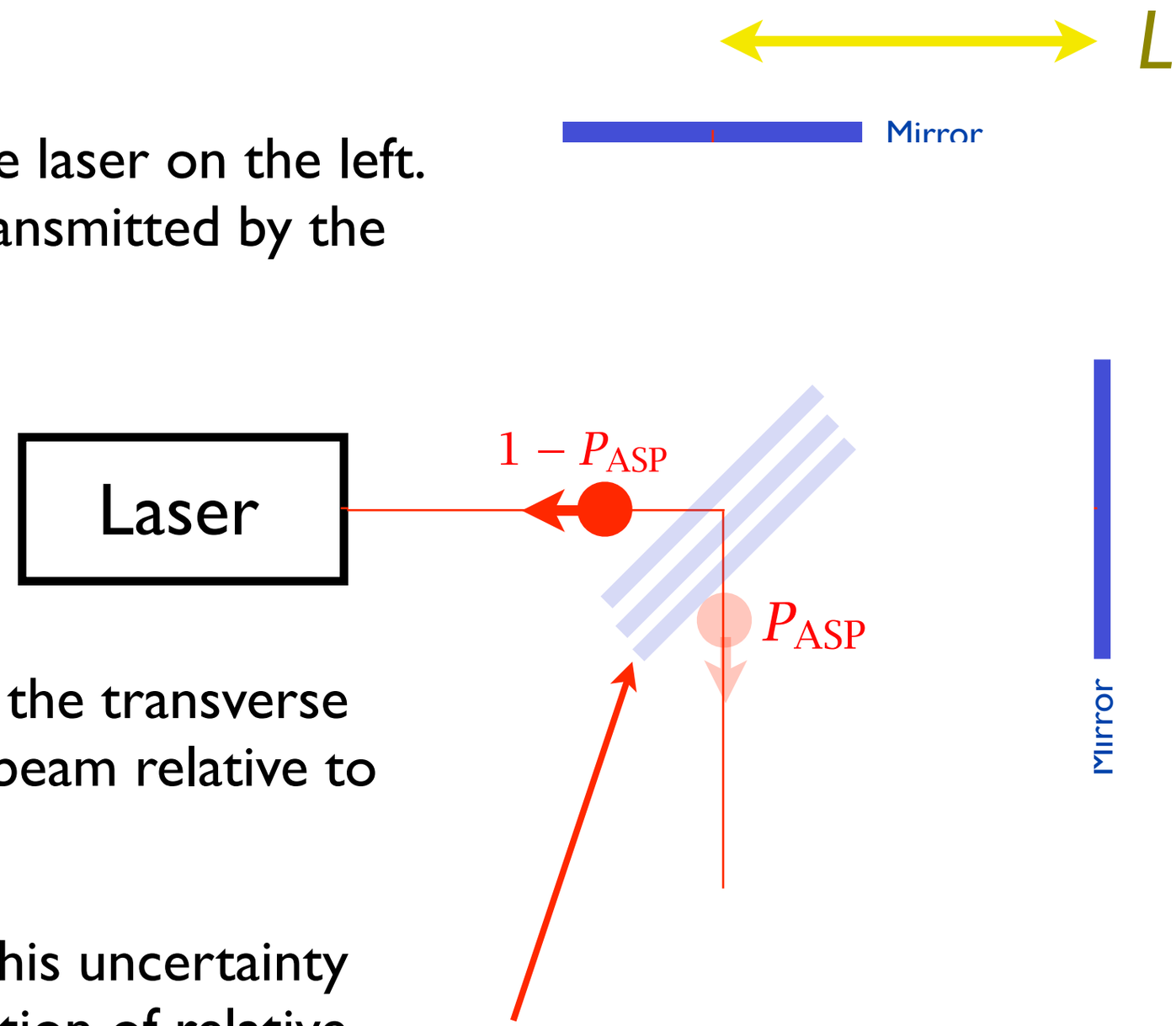
$$x = L_1 - L_2$$


Interferometer ASP Output
Light Output
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0
Arm Length Difference (microns)


Light Output
0.0040
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
−10
−5
0
5
10
Arm Length Difference (nanometers)
$\left.\frac{dP}{dx}\right|_{x_0}$
P_0
x_0

Holographic signal in a Michelson Interferometer

A photon comes in from the laser on the left. It both reflects off, *and* is transmitted by the beamsplitter.



During the light travel time, the transverse position uncertainty of the beam relative to the beamsplitter grows.

When the photon returns this uncertainty results in a broader distribution of relative phase.

The probability of exiting the system via the AntiSymmetric Port (ASP) is modified.

On return the relative position uncertainty of the beamsplitter relative to the beam has grown by

$$\Delta x = \sqrt{\frac{2 l_P L}{2\pi}}$$

The nature of the signal

The expected holographic position noise signal is broadband but the interferometer itself has a transfer function that generates autocovarience.

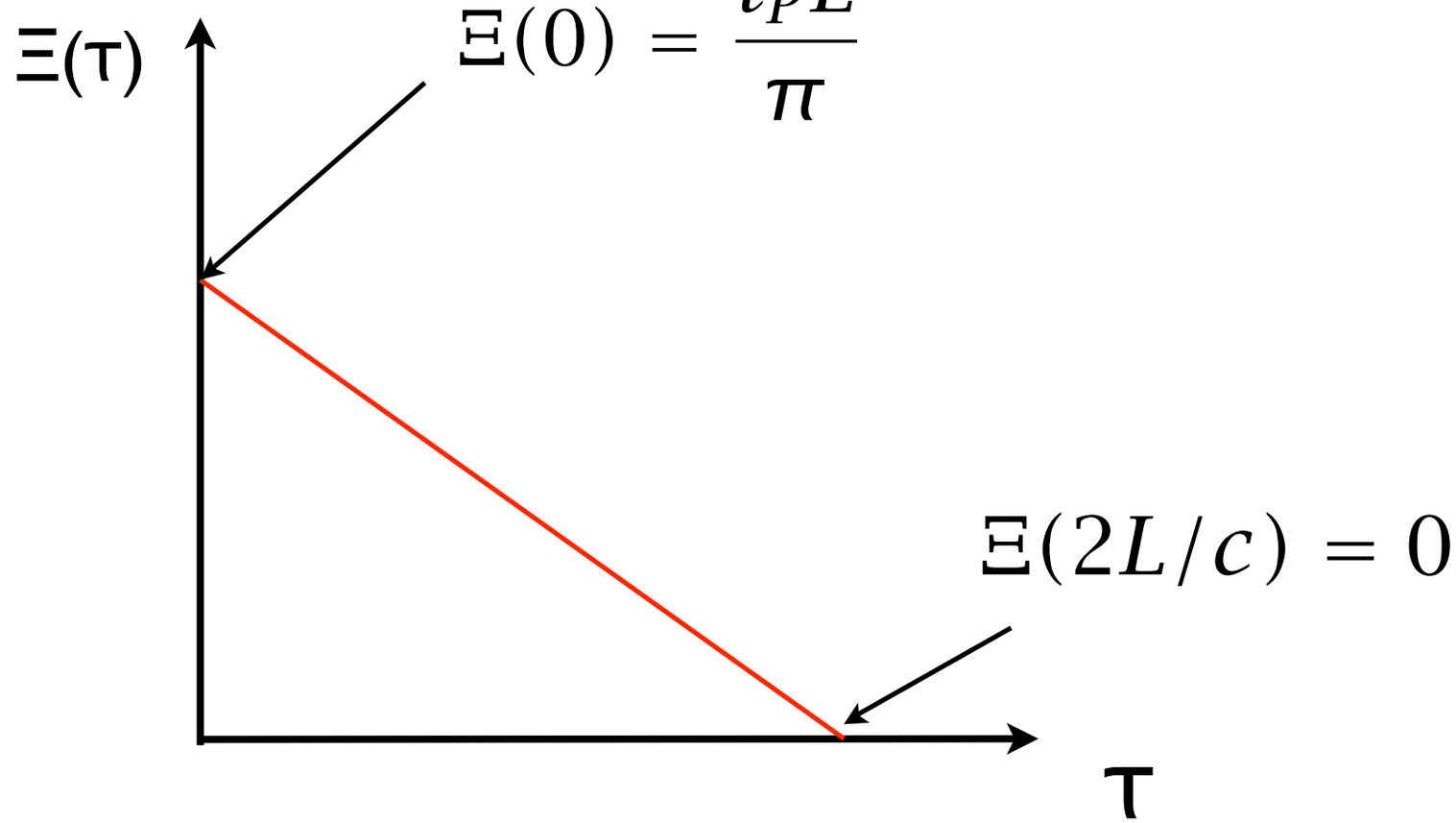
Photons that are in the interferometer at overlapping times are expected to share some of the variations. Photons separated in time greater than the round-trip time have phase delays due the holographic effect that are uncorrelated.

The time it takes a photon to go 40 m and back means the measurements can be made at about 4 MHz.

The zero lag signal is the total variation. When the lag is longer than the round-trip travel time in the interferometer, the correlation is zero.

$$\Xi(\tau) = \langle x(t)x(t-\tau)\rangle$$

$$\left\langle x_\perp^2 \right\rangle^{1/2} \equiv \Xi(0)^{1/2}$$



The time it takes a photon to go 40 m and back means the measurements can be made at about 4 MHz so the linear noise density is

$$|\tilde{\Xi}|^{1/2} = 2 \times 10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$$

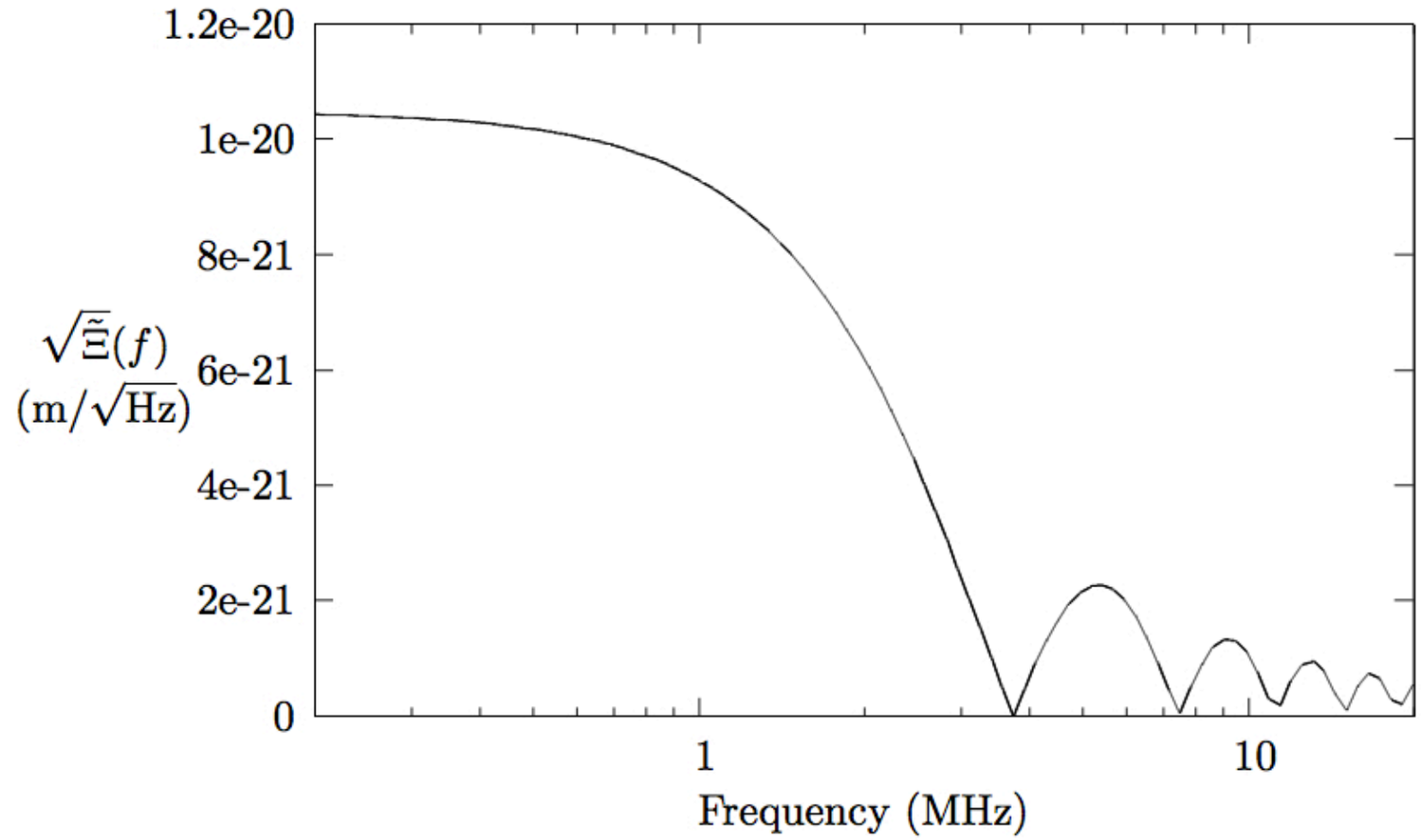
for comparison, the LIGO differential arm length noise density is

$$8 \times 10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$$

LIGO is not sensitive to transverse position at this sensitivity level. However, the fringe sensitivity is demonstrated. The holographic noise experiment can be done without inventing a new instrument.

The spectral density

The power spectral density describes how much fluctuation power is at each frequency. It is the Fourier Transform of the correlation function shown on the previous page.



The spectral noise density shape is dictated by the transfer function of the instrument. Seeing this shape, including nulls at frequencies, $f=c/2L$, will be an important indicator that the signal is understood.

The spectrum from the instrument will be this curve plus the uncorrelated noise that is reduced with integration time.

Conventional noise in an interferometer

The conventional quantum noise in an interferometer is "shot noise," the minimum noise from a "rain" of discrete photons,

$$\Delta n = \sqrt{n}$$

the Heisenberg uncertainty principal for a coherent state in an interferometer arm is

$$\Delta n \cdot \Delta\Phi \sim 1$$

so the phase spectral density from shot noise is

$$\begin{aligned}\Phi_{\text{shot}} &= \frac{1}{\sqrt{\dot{n}}} \\ &= \sqrt{\frac{h\nu}{P_{\text{BS}}}} \\ &= 9.6 \times 10^{-12}\,\text{radian}/\sqrt{\text{Hz}}\end{aligned}$$

$$\boxed{1.5 \times 10^{-18}\,\text{m}/\sqrt{\text{Hz}}}$$

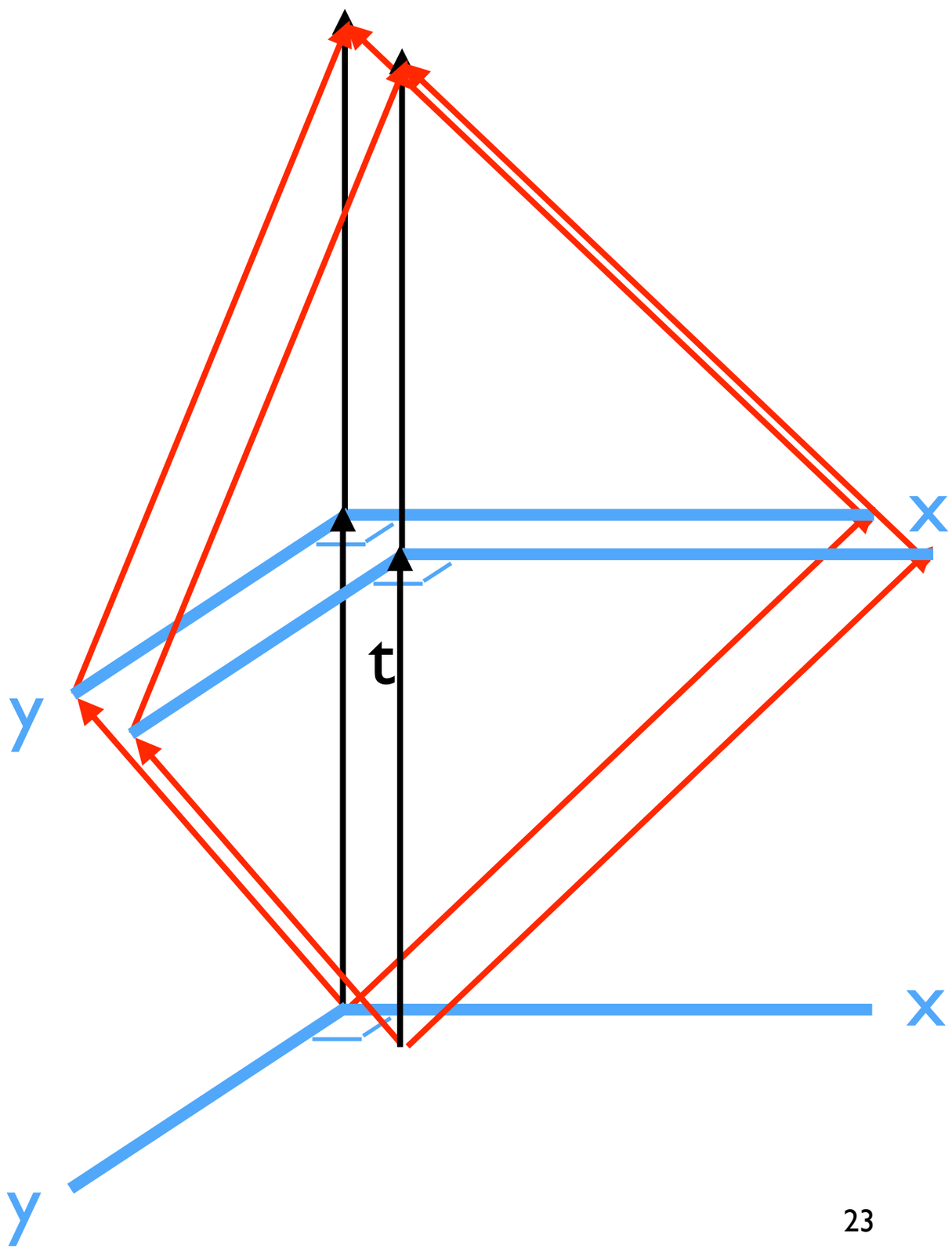
for P_{BS} =1 kW
1 μm wavelength

Reaching the signal

The shot noise is larger than the holographic signal.

$$\frac{\Phi_{\text{shot}}}{\Delta\Phi} = 160$$

The low S/N ratio can be overcome by cross-correlating two interferometers.



Two interferometers in close proximity should have correlated holographic noise.

Integration time

The shot noise is larger than the holographic signal.

$$\frac{\Phi_{\text{shot}}}{\Delta\Phi} = 160$$

The low S/N ratio can be overcome by cross-correlating two interferometers.

The holographic signal is correlated between the two instruments while the shot noise is uncorrelated. By sampling the noise many times, we can reduce the uncorrelated part:

$$d\phi_1 \times d\phi_2 = \left\langle (d\Phi^{\text{corr}})^2 \right\rangle + \frac{2}{\pi}\frac{1}{\sqrt{N}} \left\langle (d\phi^{\text{uncorr}})^2 \right\rangle$$

Integration time continued

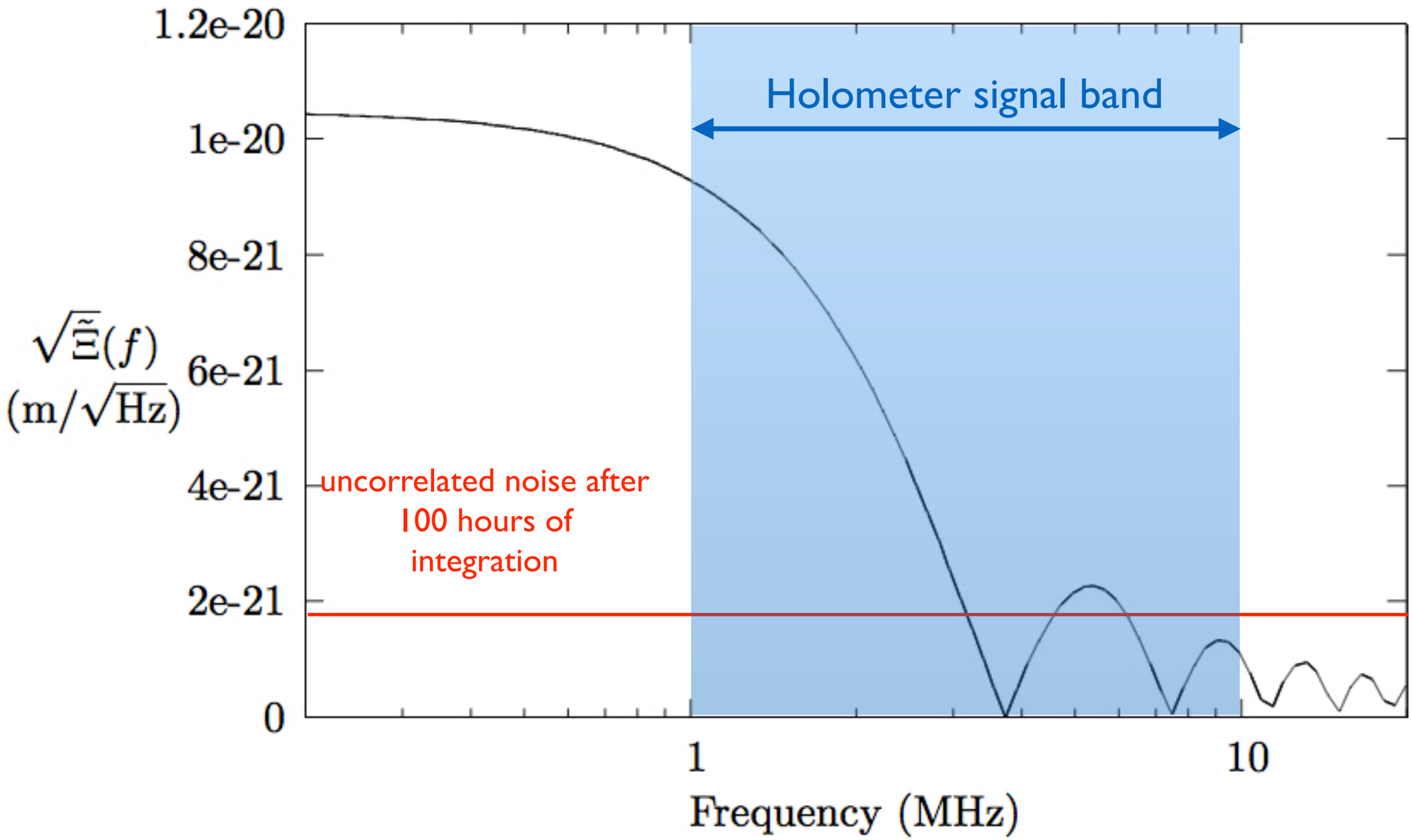
Solving, number of samples needed to get to a S/N ratio of 1 is $N = 4 \times 10^8$.

Each light crossing time of the interferometer gives an independent measure so $\tau_{sample} = 3 \times 10^{-7}$ seconds.

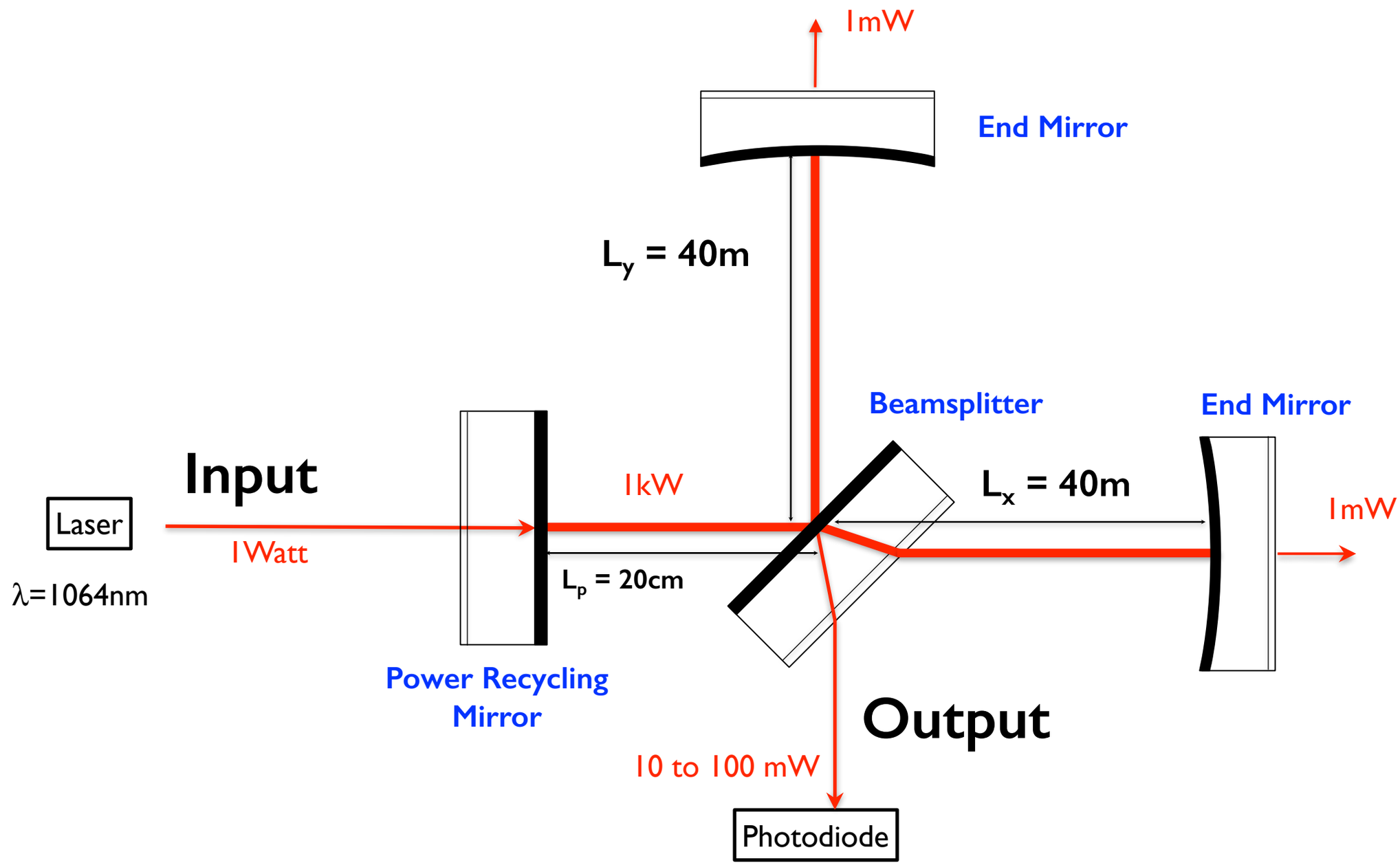
The time it takes to get to a S/N ~ 1 is

$$t_{\mathrm{int}} = N \cdot \tau_{\mathrm{sample}}$$

$$= 63\mathrm{s}$$

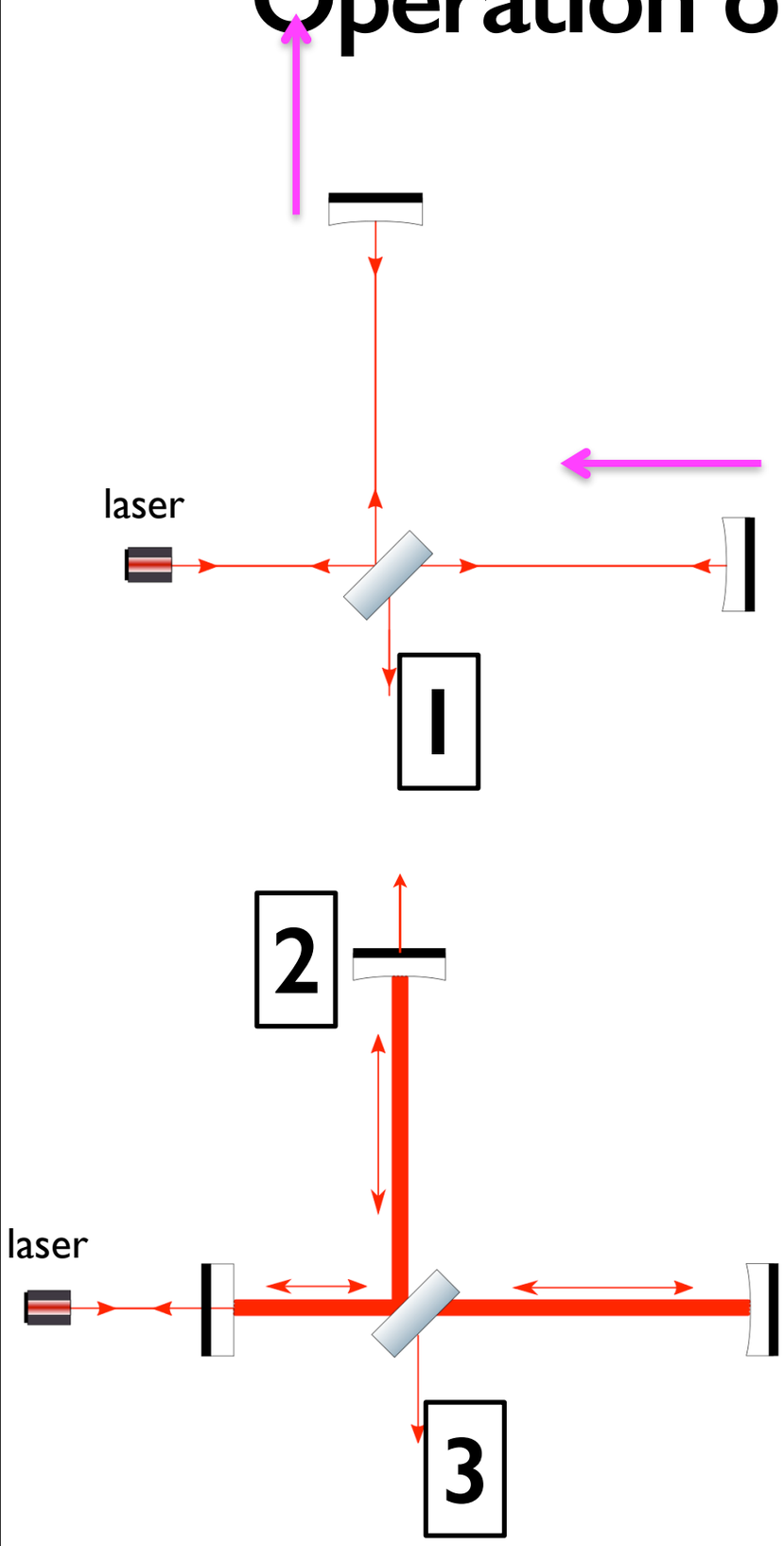

1.2e-20
1e-20
8e-21
6e-21
4e-21
2e-21
0
$\sqrt{\tilde{\Xi}(f)}$
$(\mathrm{m}/\sqrt{\mathrm{Hz}})$
Holometer signal band
uncorrelated noise after
100 hours of
integration
1
10
Frequency (MHz)

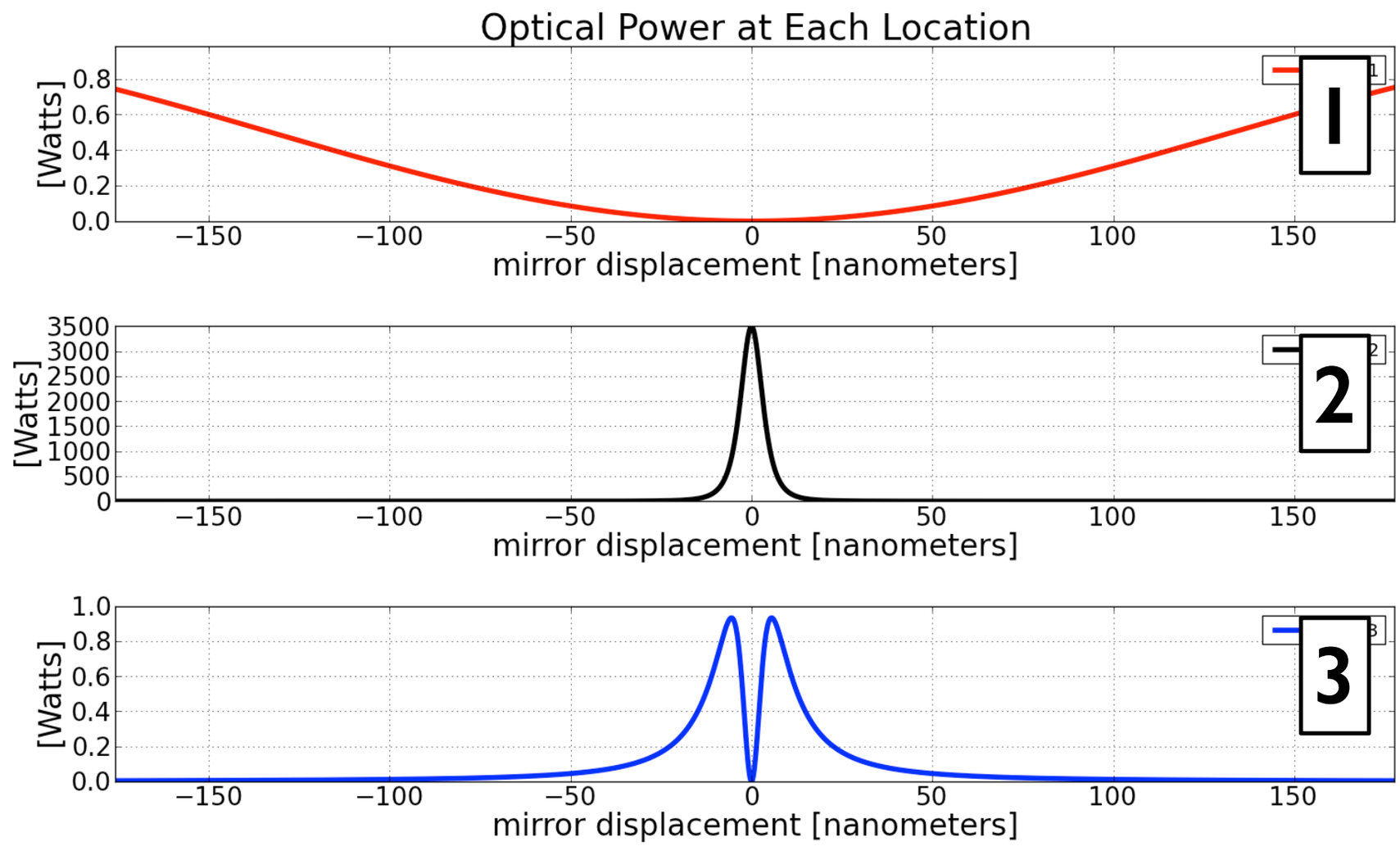
Power Recycled Michelson Interferometer



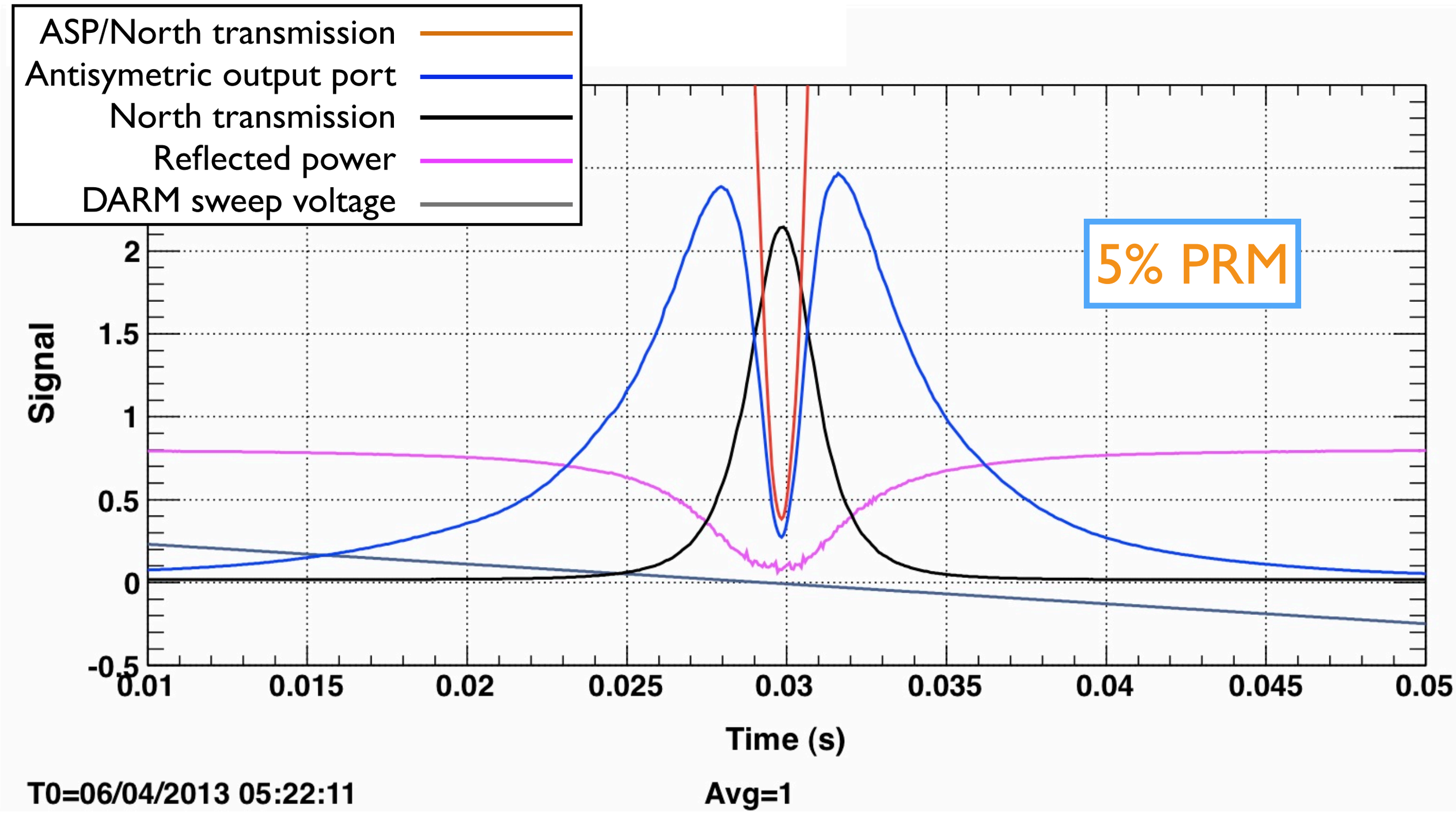
2 of these

Operation of power recycled interferometer

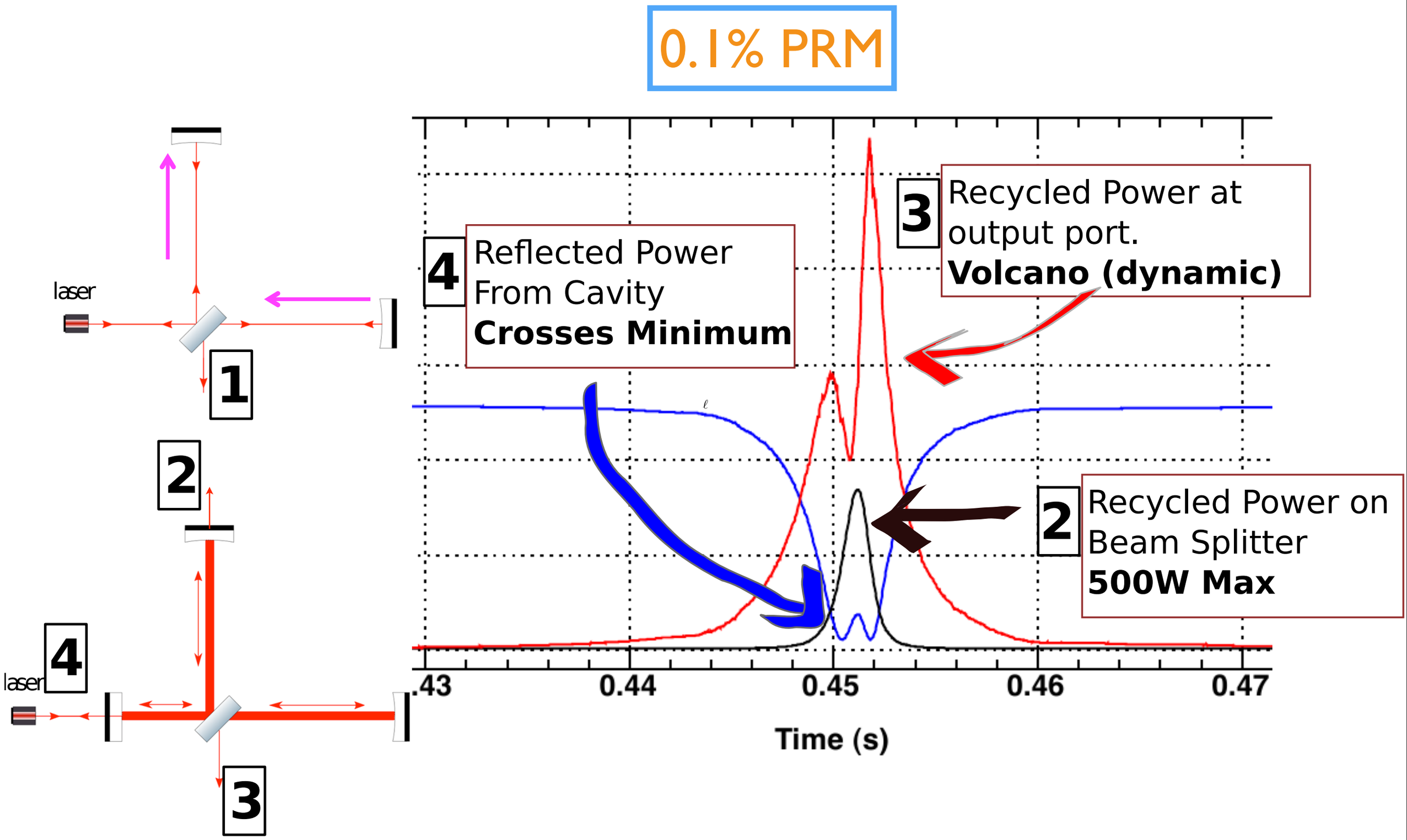




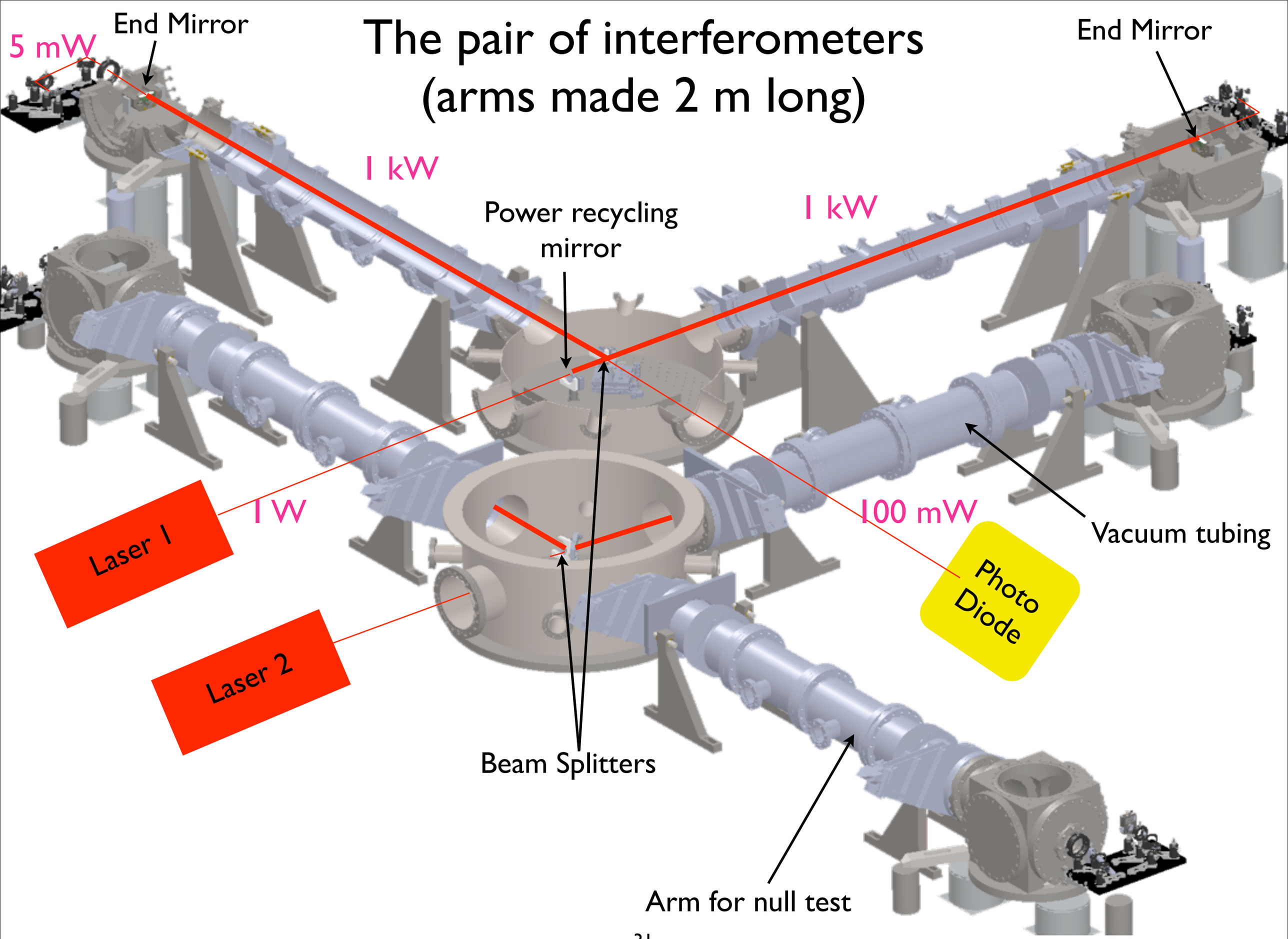
A sweep through arm length differences on an oscilloscope



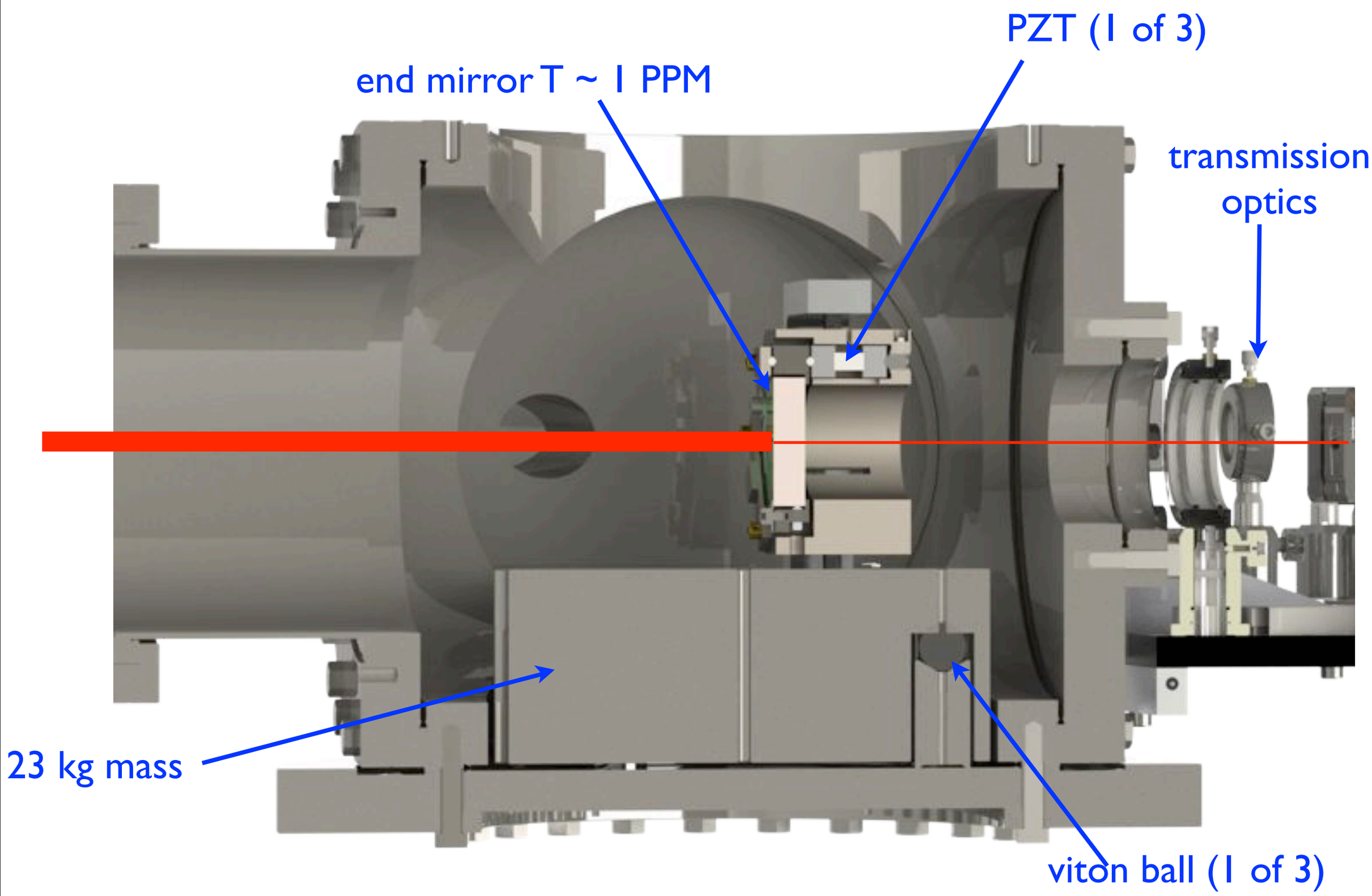
A sweep last fall with final power recycling mirror

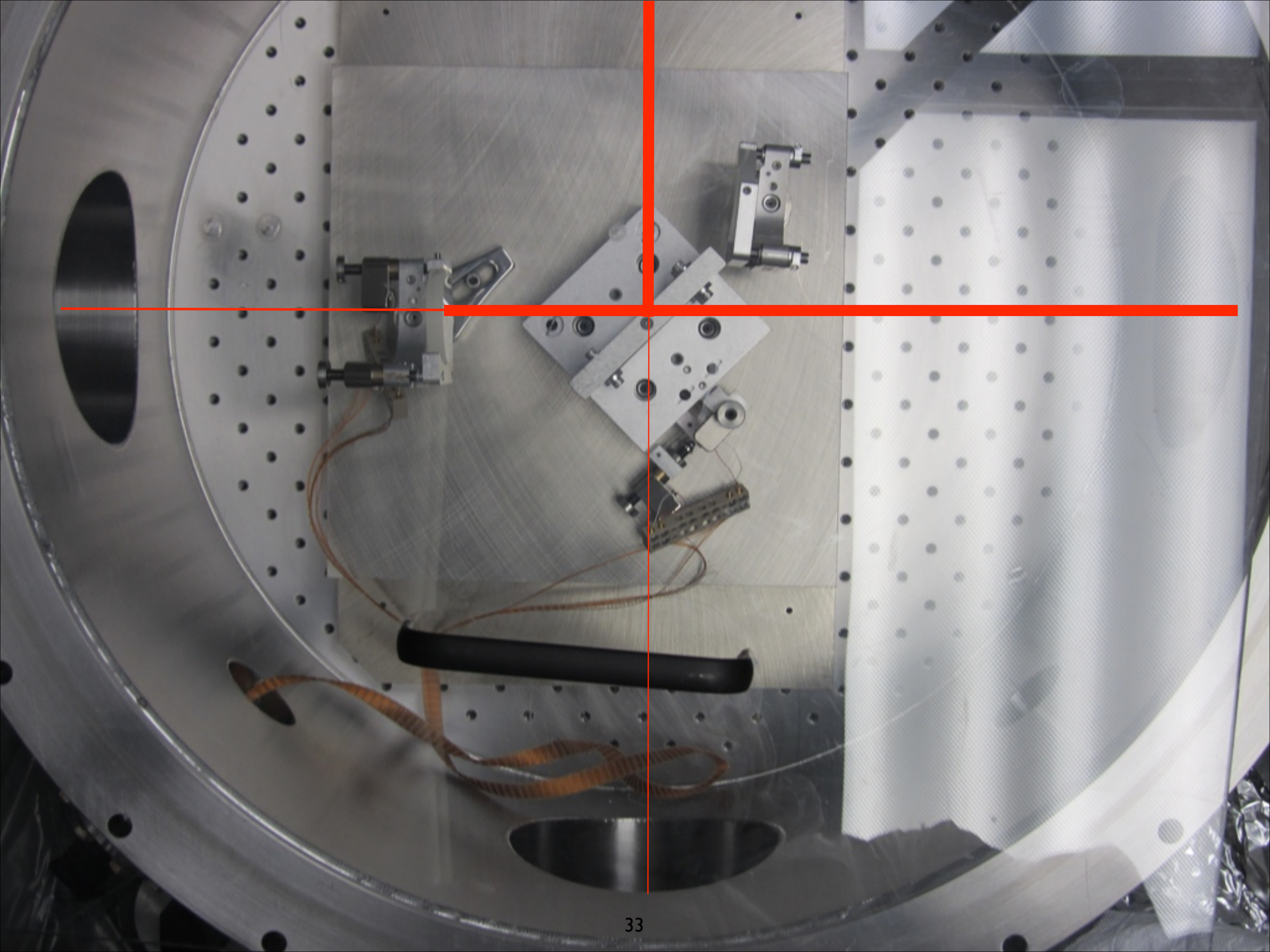


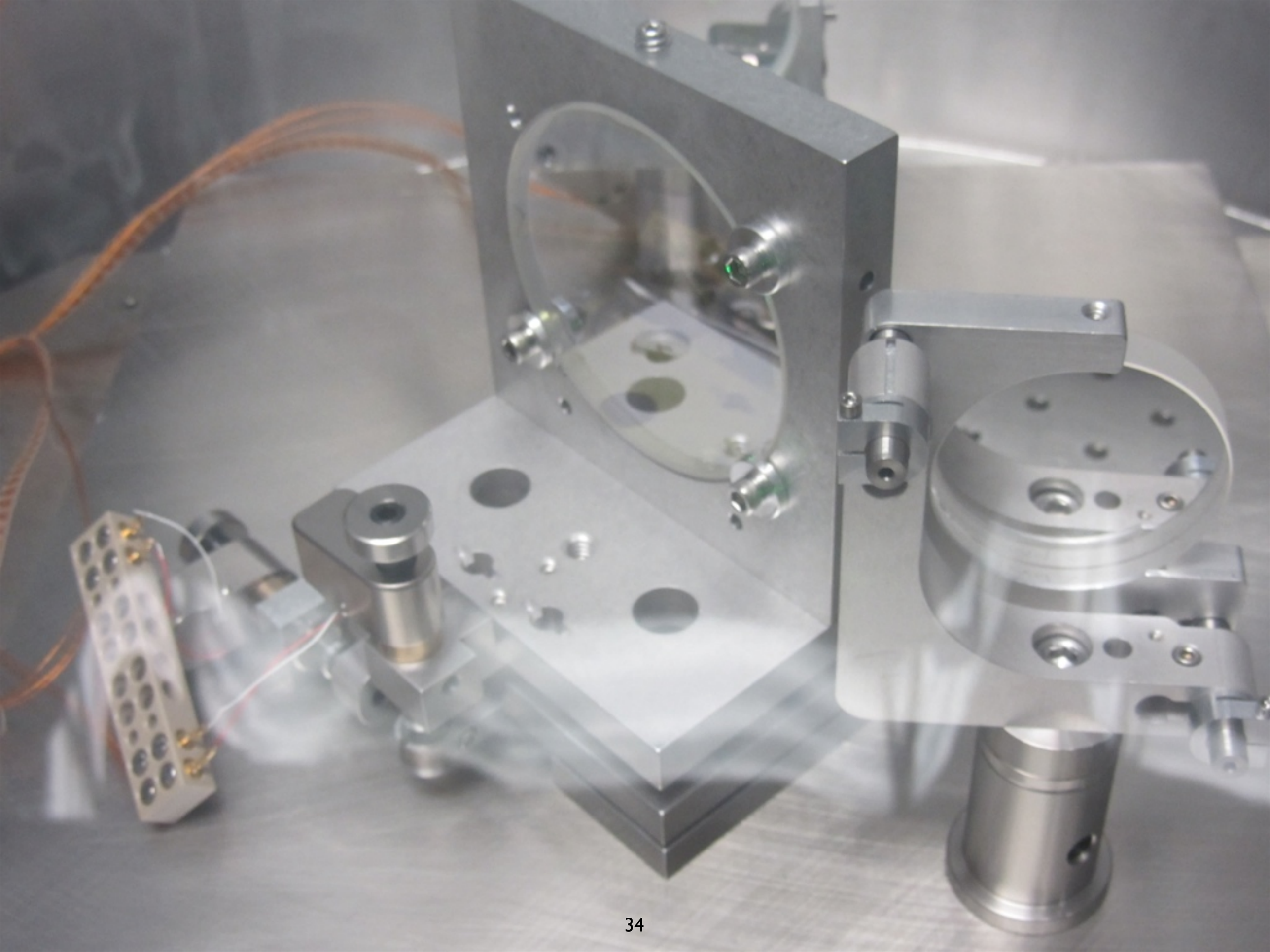
The pair of interferometers (arms made 2 m long)



End station optics and vibration isolation

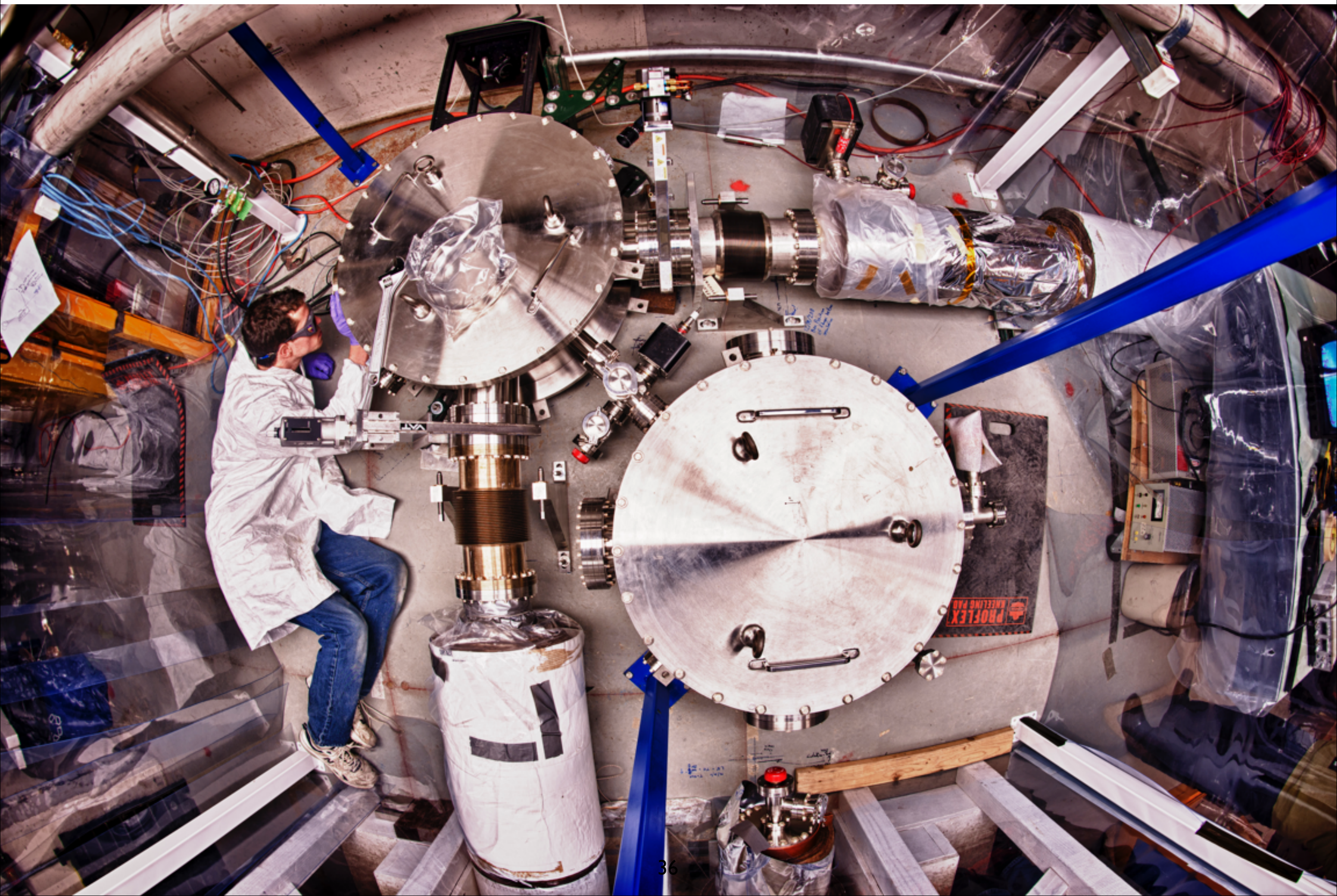






The Holometer is located in a meson beamline

Center stations of the Holometer



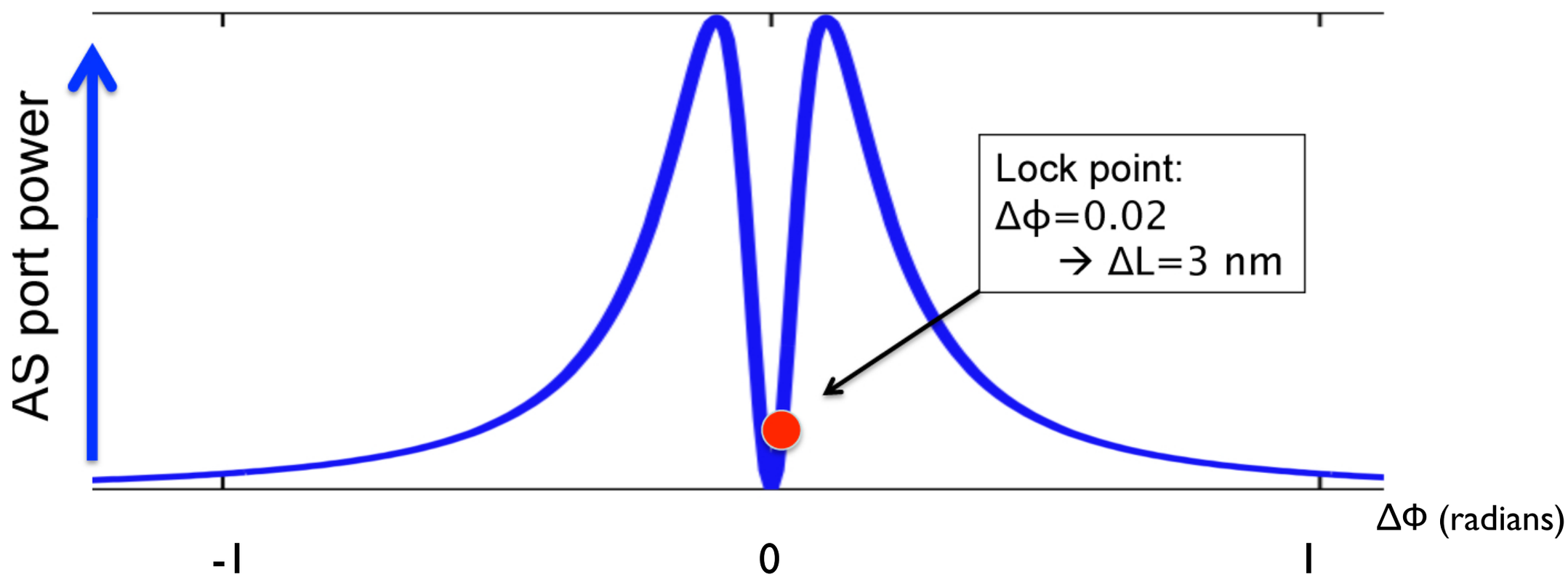
ACCELERATOR DIVISION
HYDROSTATIC LEVEL LAB
FERMILAB HOLOMETER
Fermilab
Massachusetts Institute of Technology
University of Chicago
University of Michigan
California Institute of Technology
R-13

Holding the lock point

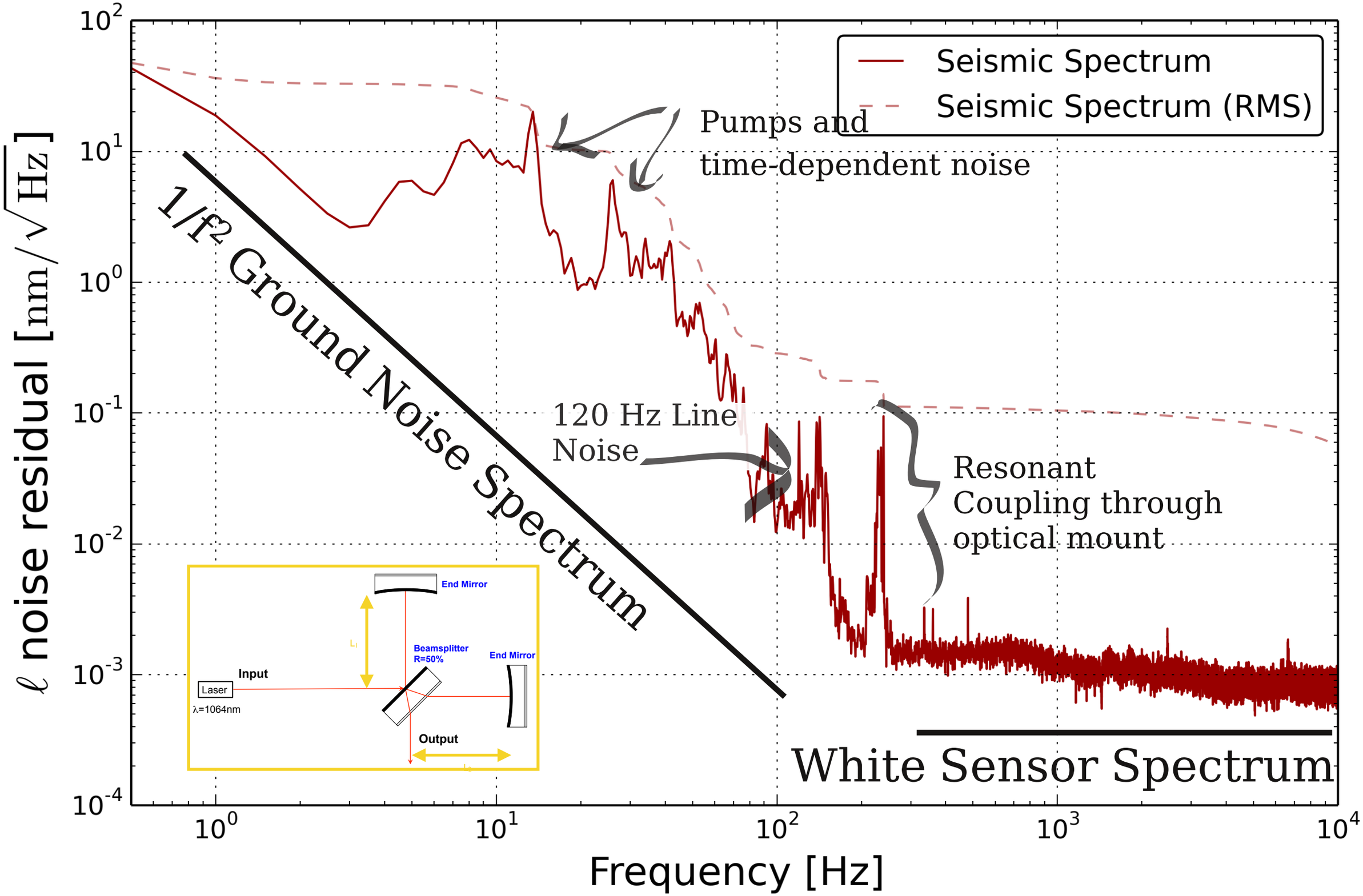
- The lock point is 3 nm from the null. One servo uses the output photodiode signal to move the end mirrors differentially to maintain a constant AS port photodiode intensity. This keeps the differential arm lengths locked (at low frequencies).

- A separate servo keeps the laser locked to the cavity using a PDH lock on the power reflected from the cavity.

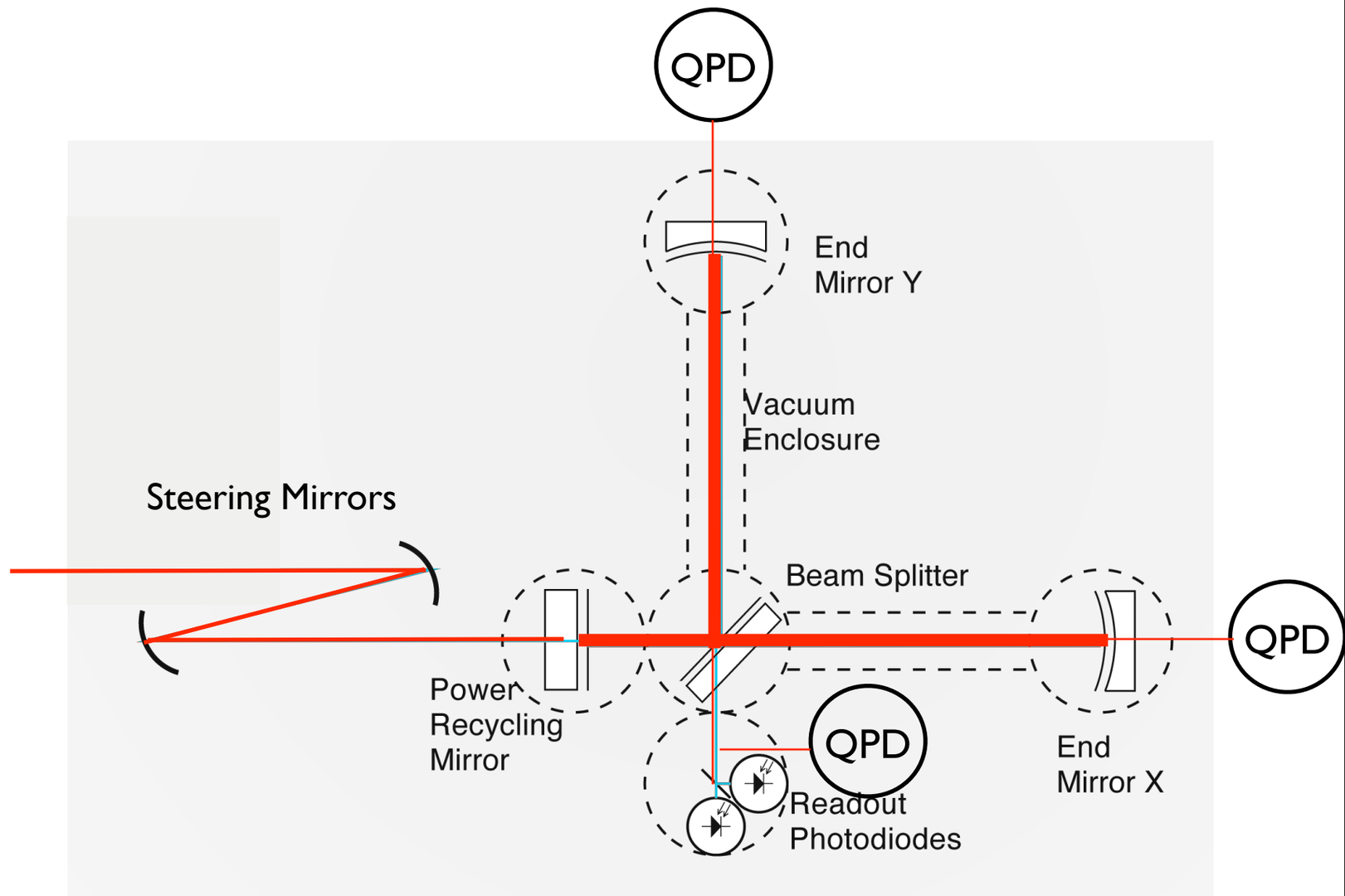
- At high frequencies (where the holographic signal is) the interferometer arm length is free to move. The photodiode signal is recorded and analyzed.



Simple Michelson ground noise test



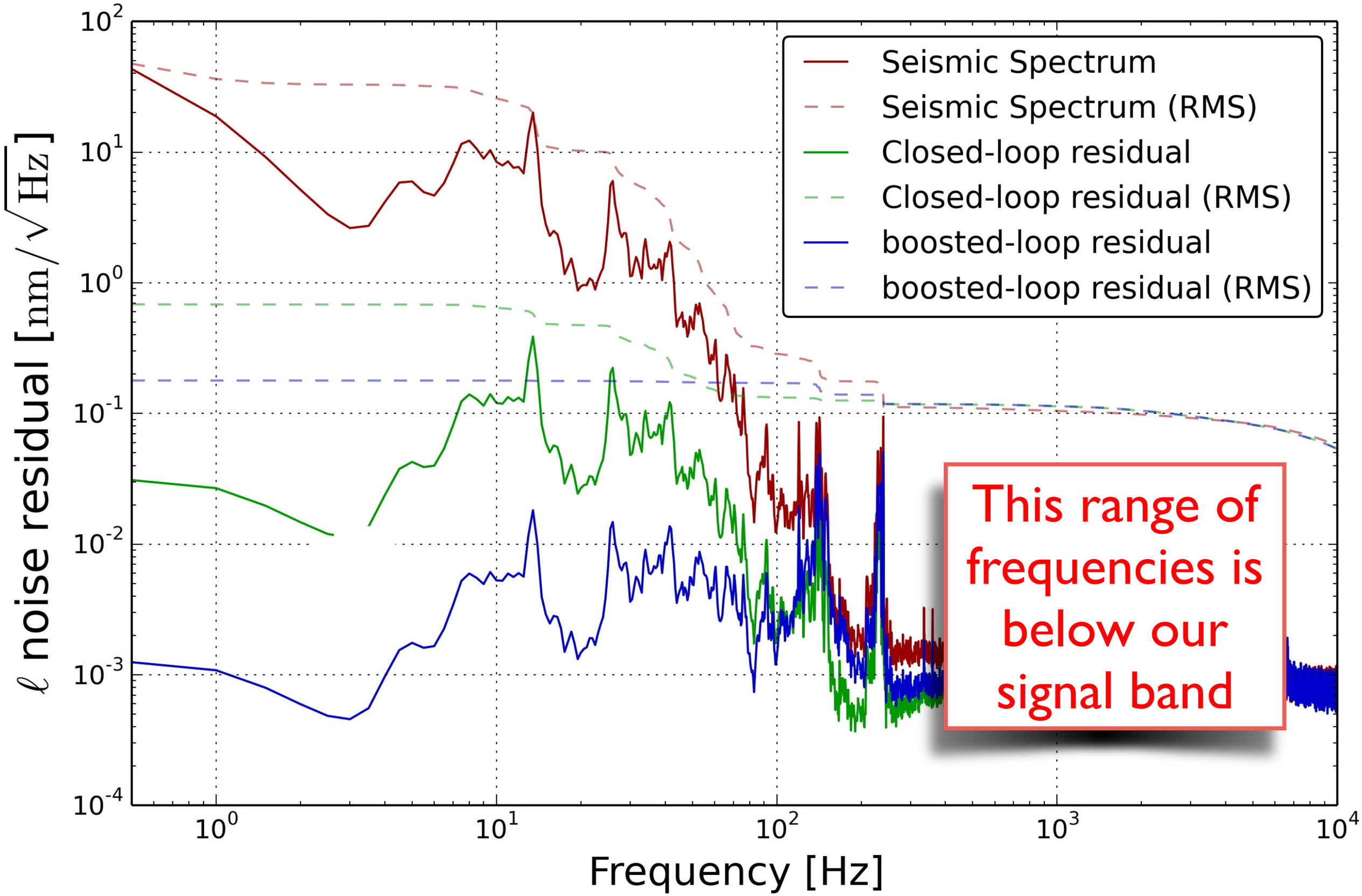
Servo System



- Main servo loop is the Differential Arm Length (DARM)
  - input is readout diodes
  - output is all 6 endmirror PZTs
  - Loop UGF 1kHz
- Secondary steering loop signal derived from end station and steering mirror dither and lockin error signal.
  - input from endstation QPDs and output port QPD
  - output is steering mirror and end station PZTs
  - Low frequency <1 Hz loop.
- Frequency lock (CARM). PDH lock.
  - input from PRM reflection
  - output to endstation PZT
  - partially analog loop 10 kHz UGF

Servo System Implementation

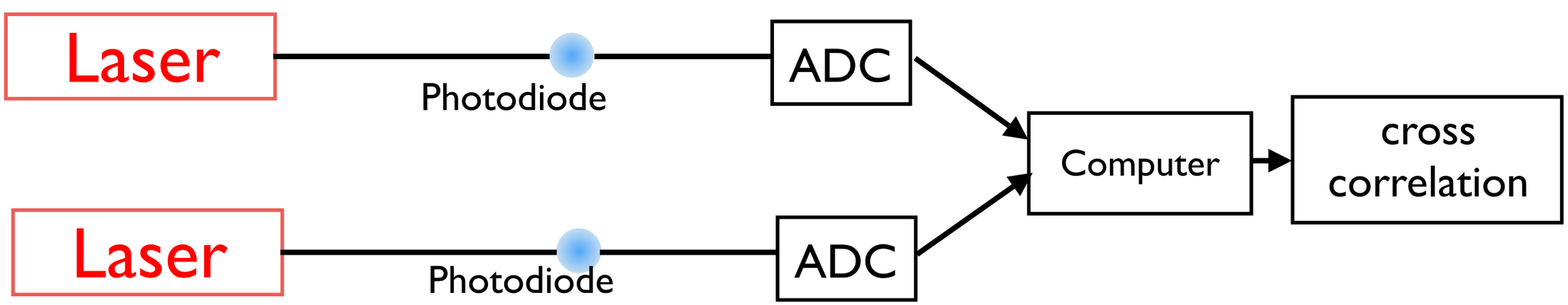
- Analog filter-buffer board 40 kHz Nyquist filter on input and output.
- 8 channel in, 8 channel out 16 bit ADC/DAC
- Loop filters, modulation/demodulation orthogonalizing matrix implemented on Xilinx Virtex FPGA
- 130 kHz ADC downsampled to 32 kHz before loop filters. Upsampled before DAC.
- Runs 10 channel, 30 stage bi-quadric loop filters at 32 kHz.


Seismic Spectrum
Seismic Spectrum (RMS)
Closed-loop residual
Closed-loop residual (RMS)
boosted-loop residual
boosted-loop residual (RMS)
This range of frequencies is below our signal band
ℓ noise residual [nm/$\sqrt{\text{Hz}}$]
Frequency [Hz]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

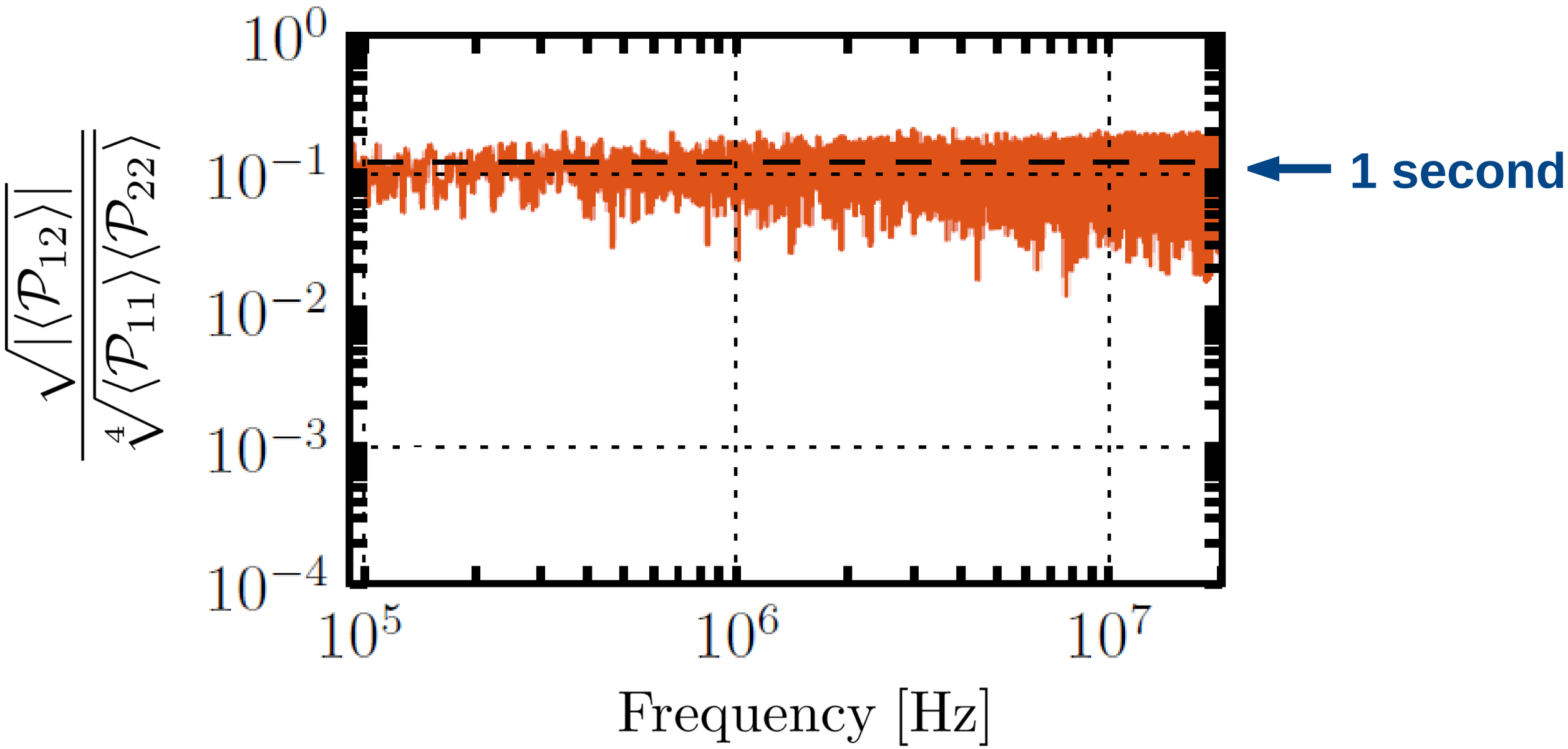
RFI and Additive Interference

RFI has the potential of introducing a post-detection correlated signal.

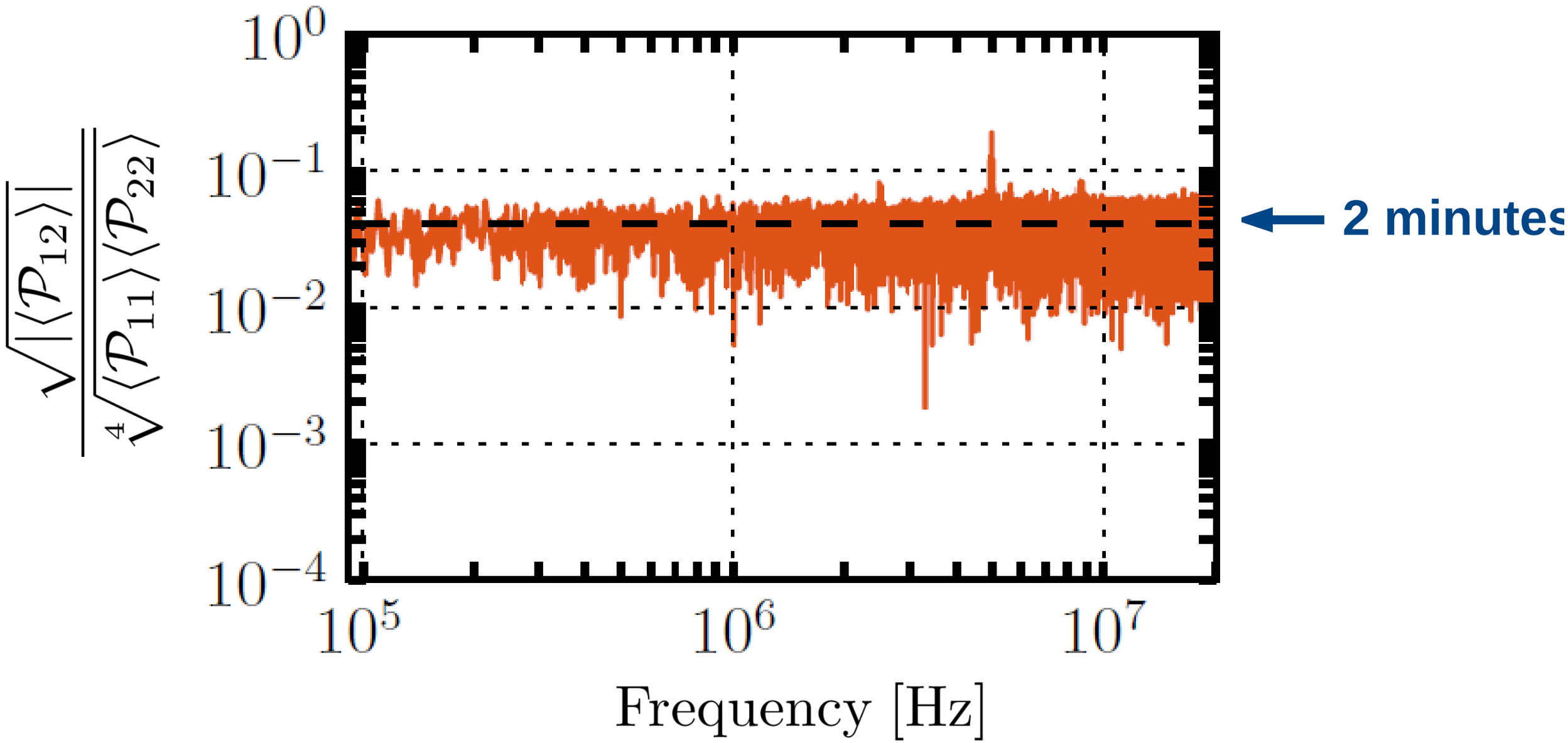
- we expect most of this can be eliminated by careful design.
- most of the power will be in lines rather than continuum
- We must run a null experiment



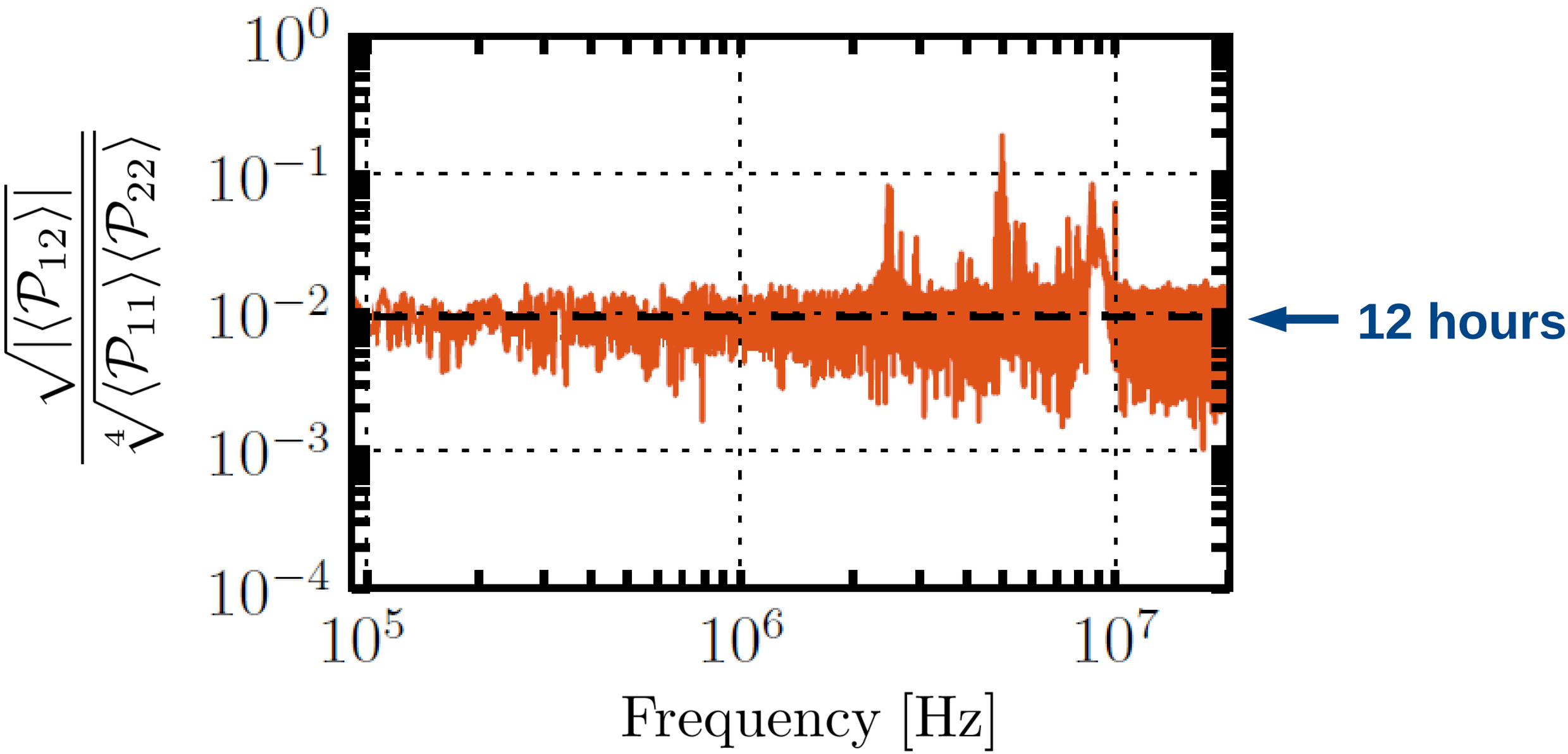
Laser Beam Correlation



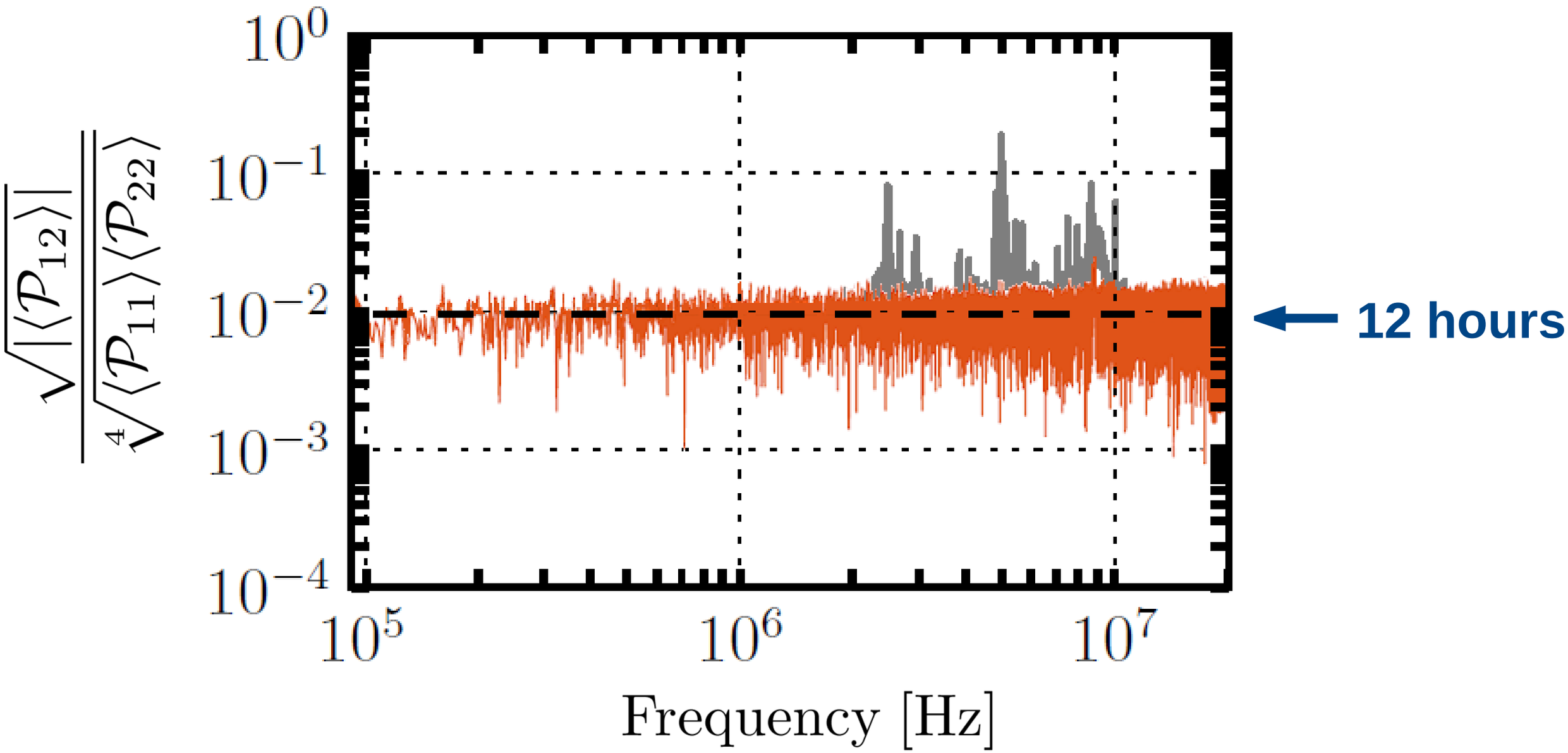
Laser Beam Correlation



Laser Beam Correlation



Laser Beam Correlation

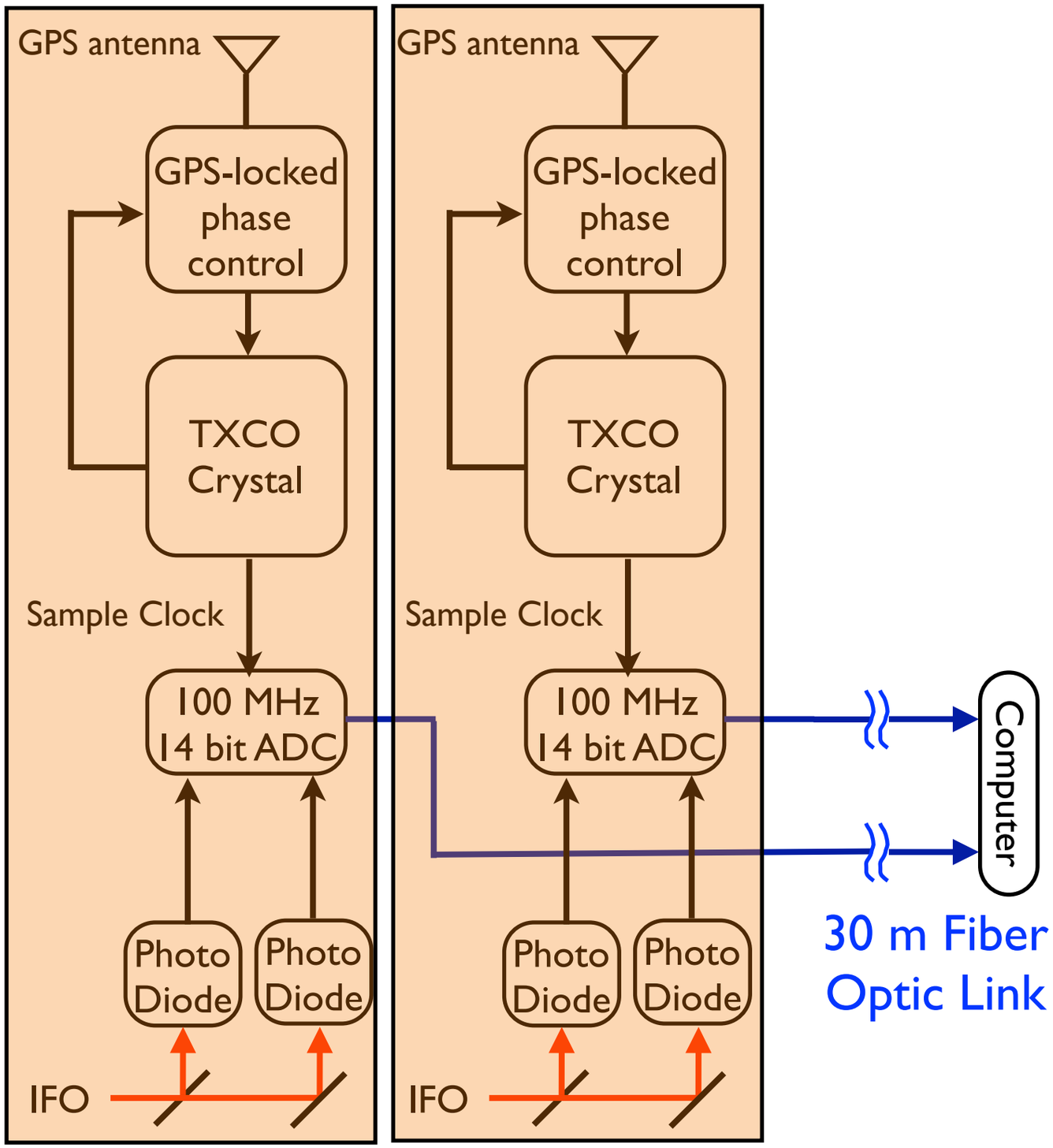


Signal Sampling Issues

- The antisymmetric output port signal is highly 1/f even with a strong low-frequncy servo lock.
- Correlated sample phase jitter at MHz frequencies can generate a correlated signal.
- We operate with separately clocked ADCs independently slaved to GPS timing.

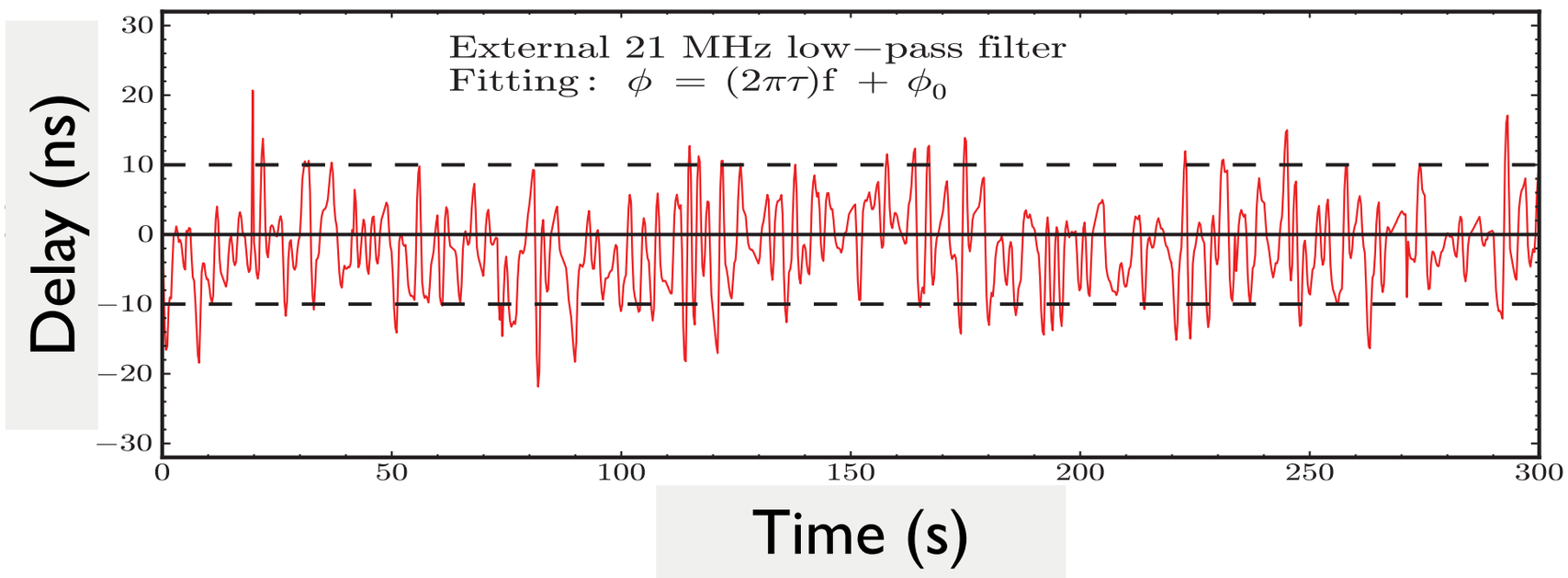
Fast Digitization Systm

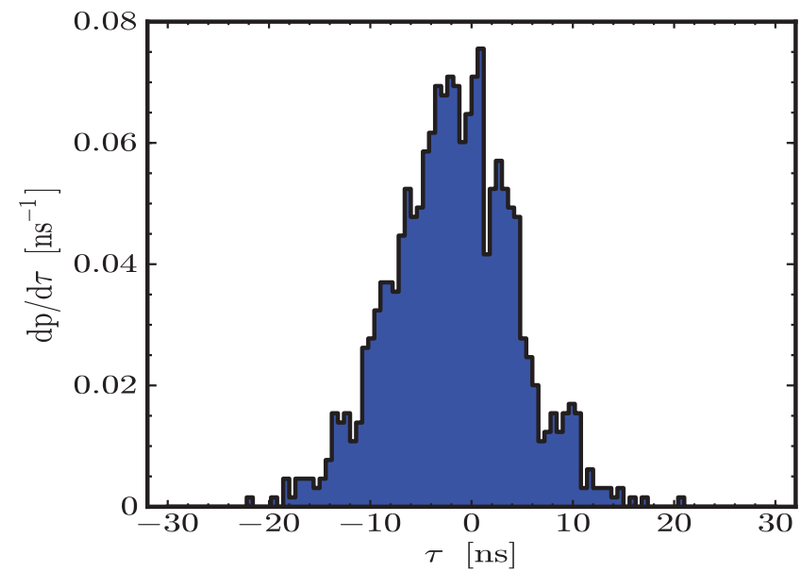
- Each interferometer output is digitized with an isolated electrical system
- The sample clocks are independently referenced to GPS
- The analysis computer is 30 m distant and connected over a fiber-optic digital link.



Current System Phase Noise

Delay for each 40 ms frame





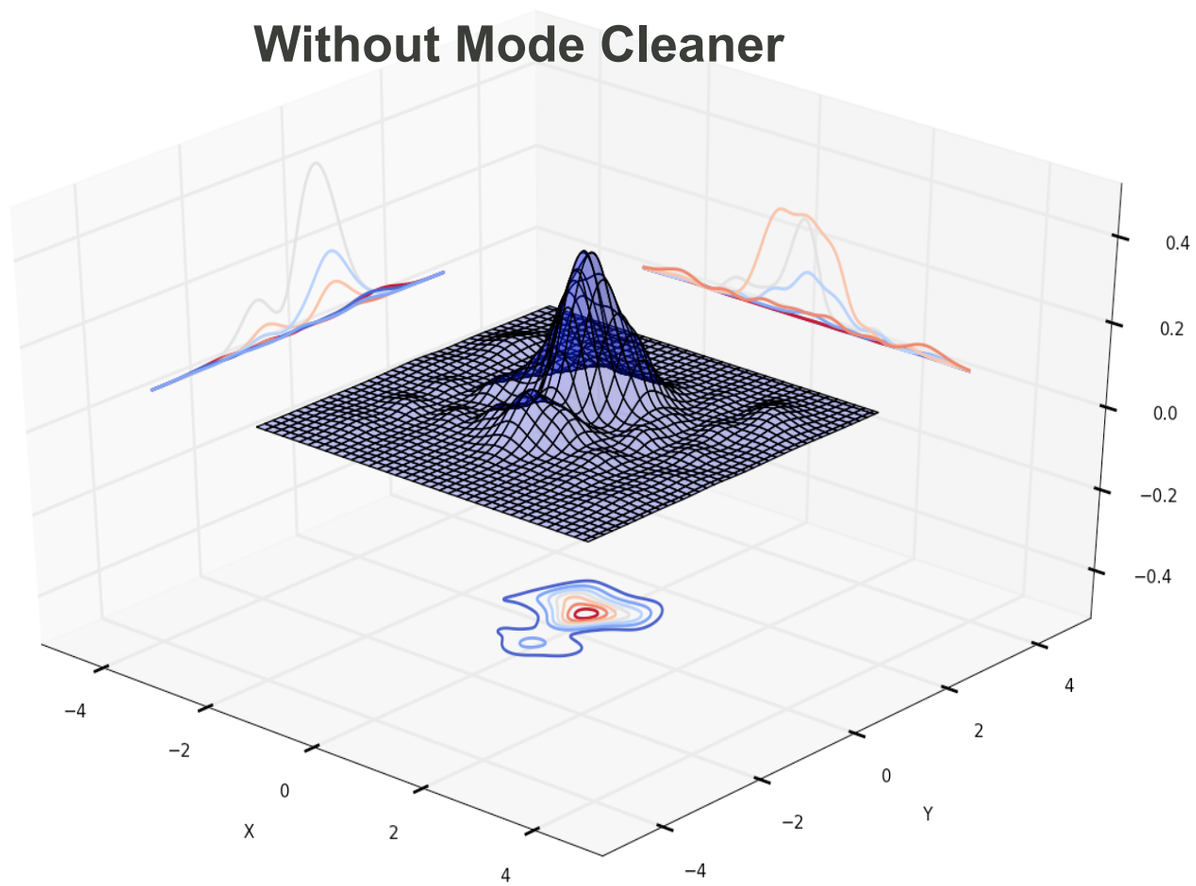
The current clock servo system restricts the timing jitter an amplitude of less than 10 ns but not in an optimized way.

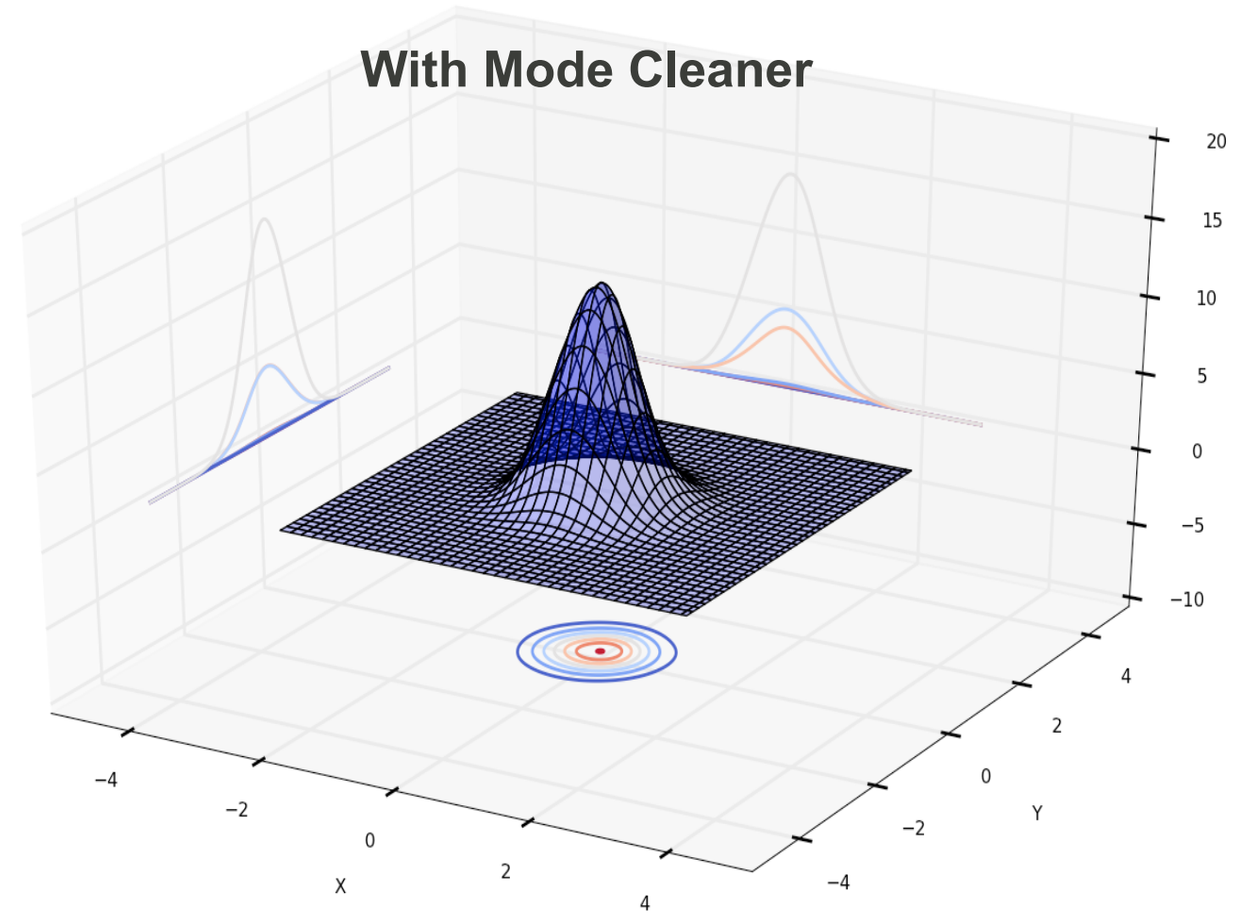
Without further correction, the phase jitter at 10 MHz is < 20°.

Null Defect

One major remaining uncertainty is the level of an interferometer null defect: the inability to completely null the output at zero delay.

- Imbalance in endmirror reflectance
- Imbalance in endmirror figure
  - radius difference
  - figure difference - higher order modes.
- Beamsplitter figure





How do we know if it is holographic noise?

The holographic noise has a predicted spectral shape

The normalization of the spectrum scales as L^2.

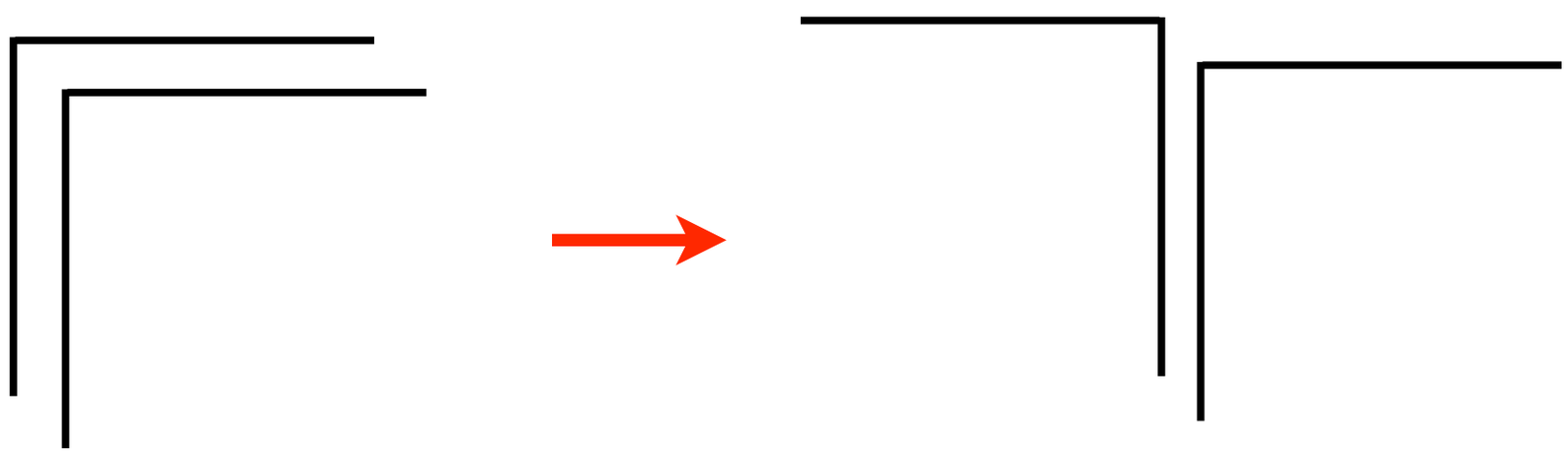
The interferometer response function has a known shape and cuts off at $f=c/2L$.

Convention RF backgrounds are usually frequency dependent - narrow lines, 1/f...

This gives us a way to discriminate against conventional backgrounds such as radio stations.

Experimental tests:

Move the two interferometers to operate in a null configuration.



Summary

- The holometer is designed to probe properties of space-time using power-recycled laser interferometry.

- Construction is complete
  - Completed the vacuum system.
  - Servo control is in place.
  - Operating with final optics.
  - Two interferometers routinely locked at >1kW.

- Commissioning is starting
  - Scripting servo system to make locking and operation routine.
  - Noise and correlated noise under control.
  - Optical defect being studied. Mirror swap to minimize.
  - Output mode cleaner being implemented.
  - Calibration system in design.

- We plan to begin taking data at full sensitivity this calendar year.