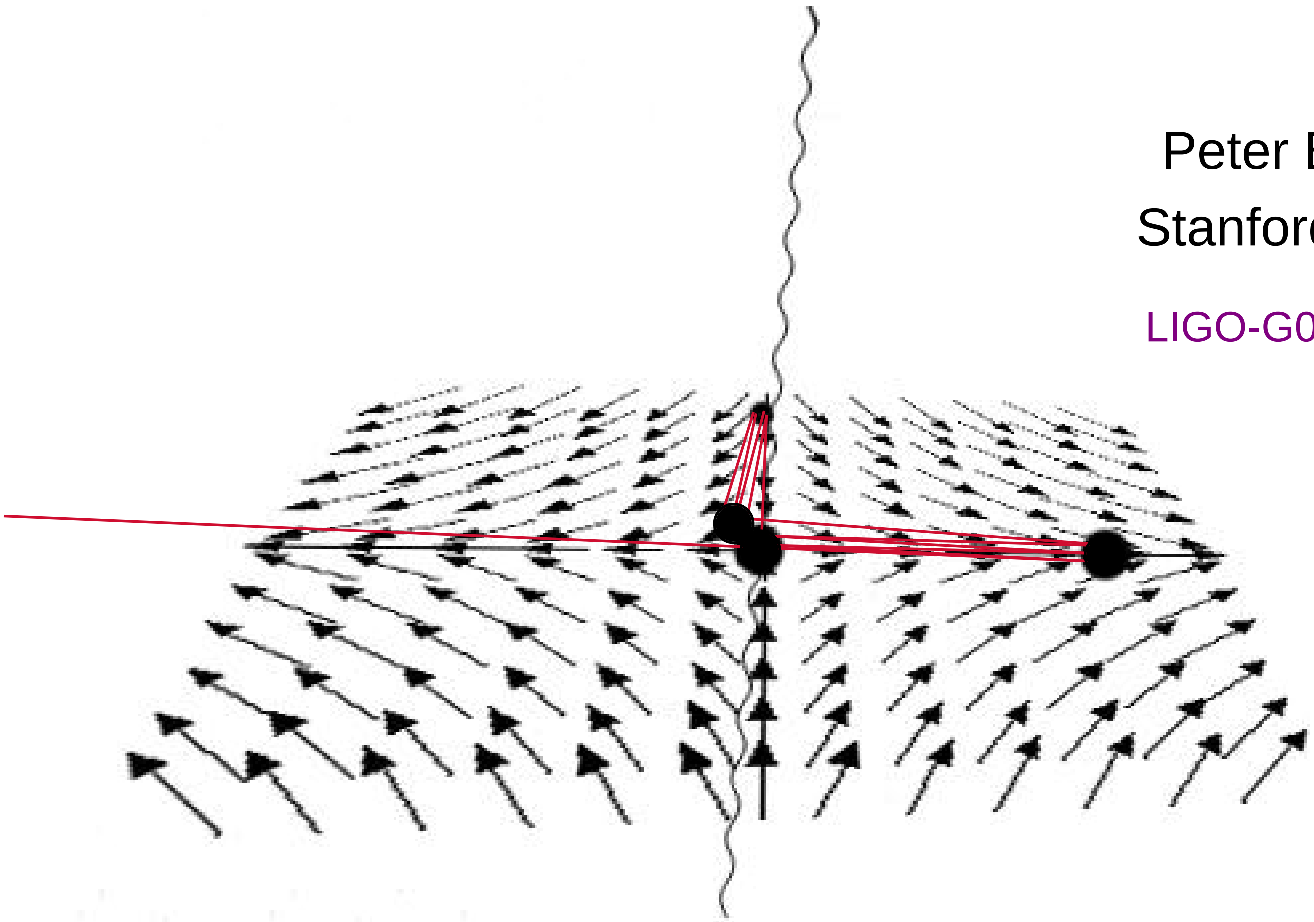
Progress on the Sagnac Interferometer for Gravitational Wave Detection

(An interferometer for thermally loaded operation)



Peter Beyersdorf

Stanford University

LIGO-G000057-00-D

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Questions this talk will (hopefully) answer

- Why use a Sagnac interferometer for high-power interferometry?
- What challenges does high-power interferometry introduce?
- How are we addressing these challenges?
- What more needs to be done?

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Ligo III thermal loss limited sensitivity

Thermal distortions will limit the circulating power in Ligo III.

Material	Lensing β/κ (nm/W)	Expansion α/κ (nm/W)	Absorbtion (cm^{-1})	Power @ $\lambda/100$ (W)	Sensitivity h (/√Hz)
Transmissive at 300k					
Sapphire	19	147	$4 \bullet 10^{-4}$	1.5k	$3.1 \bullet 10^{-23}$
Fused Silica	17	370	10^{-5}	15k	$1.0 \bullet 10^{-23}$
Reflective at 300k					
Sapphire	-	147	-	91k	$4.1 \bullet 10^{-24}$
Silicon	-	18	-	740k	$1.4 \bullet 10^{-24}$
Fused Silica	-	370	-	36k	$6.4 \bullet 10^{-24}$
Reflective at 10k					
Copper	-	.003	-	4.5g	$1.8 \bullet 10^{-26}$
Silver	-	.006	-	2.2g	$2.6 \bullet 10^{-26}$
Aluminum	-	.012	-	1.1g	$3.7 \bullet 10^{-26}$

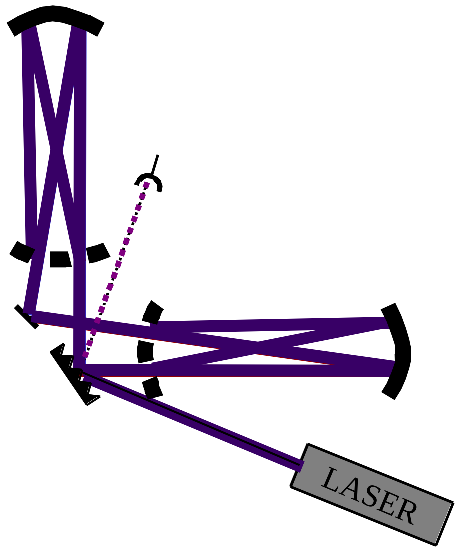
Change in Sagitta of mirrors $= \left[\frac{\alpha / \kappa}{4\pi} \left(a_{coatings} + a_{bulk} \right) + \frac{\beta / \kappa}{4\pi} a_{coatings} + 1.3 \frac{\beta / \kappa}{4\pi} a_{bulk} \right] P_{inc}$

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

What properties should an advanced interferometer have?

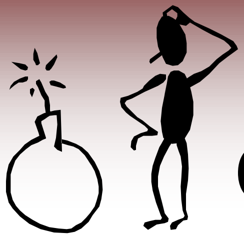
- All reflective optics
  - grating beamsplitter
  - delay lines for energy storage
- Robust control scheme
  - dynamically stable
  - soft failure mode

Straw-man design based on an all-reflective Sagnac



- Interfering beams travel a common path
  - –interferometer is passively locked
  - –output has excellent common-mode noise rejection
  - –No out-of-band control effort is necessary

THE Stanford GRAVITATIONAL WAVE GROUP

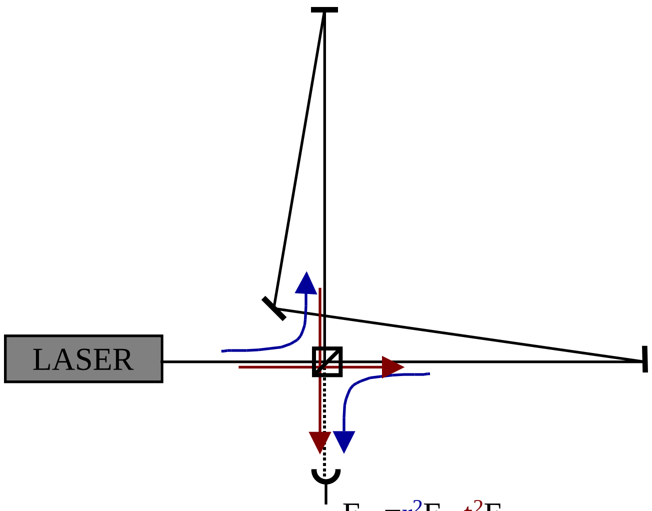


Challenges to implementing this design

- Detection of the dark fringe on the symmetric port of the beamsplitter.
- Developing a readout scheme that maintains the common path of the interfering beams.
- Reducing noise from scattered light in delay-lines.
- Handling (and generating) high circulating power
- Fabricating large mirrors for the delay lines

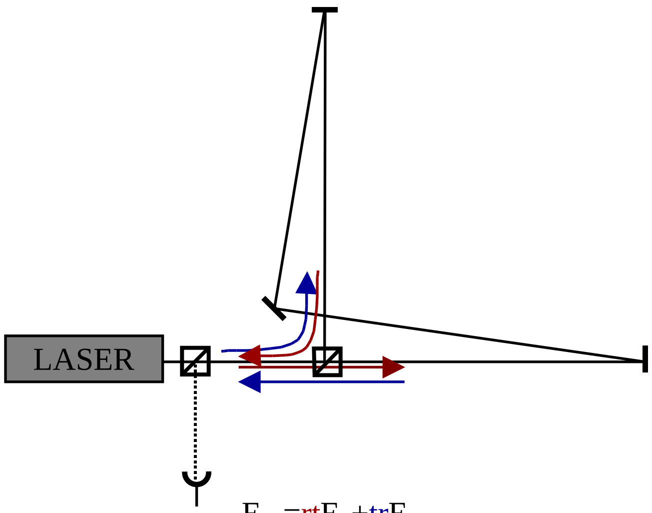
Using the Beamsplitter Symmetrically

The dark fringe in a conventional Sagnac interferometer occurs at the asymmetric port of the beamsplitter



$E_{dp}=r^2E_0-t^2E_0$

Detection on the Asymmetric port
of the beamsplitter.



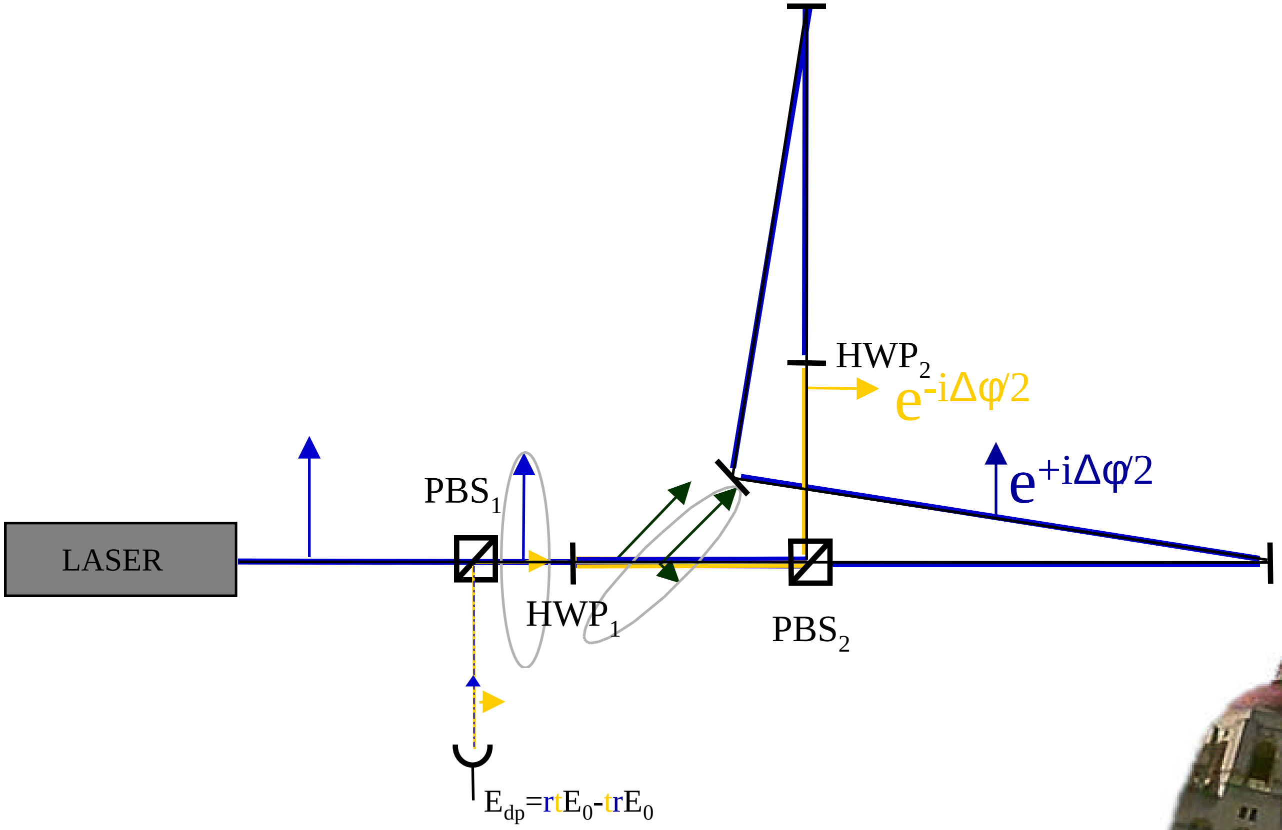
$E_{dp}=rtE_0+trE_0$

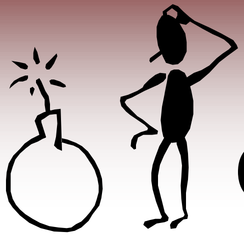
Detection on the Symmetric port
of the beamsplitter

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

The Polarization Sagnac Interferometer

Polarization control allows all light to exit the interferometer at the symmetric port of the beamsplitter.





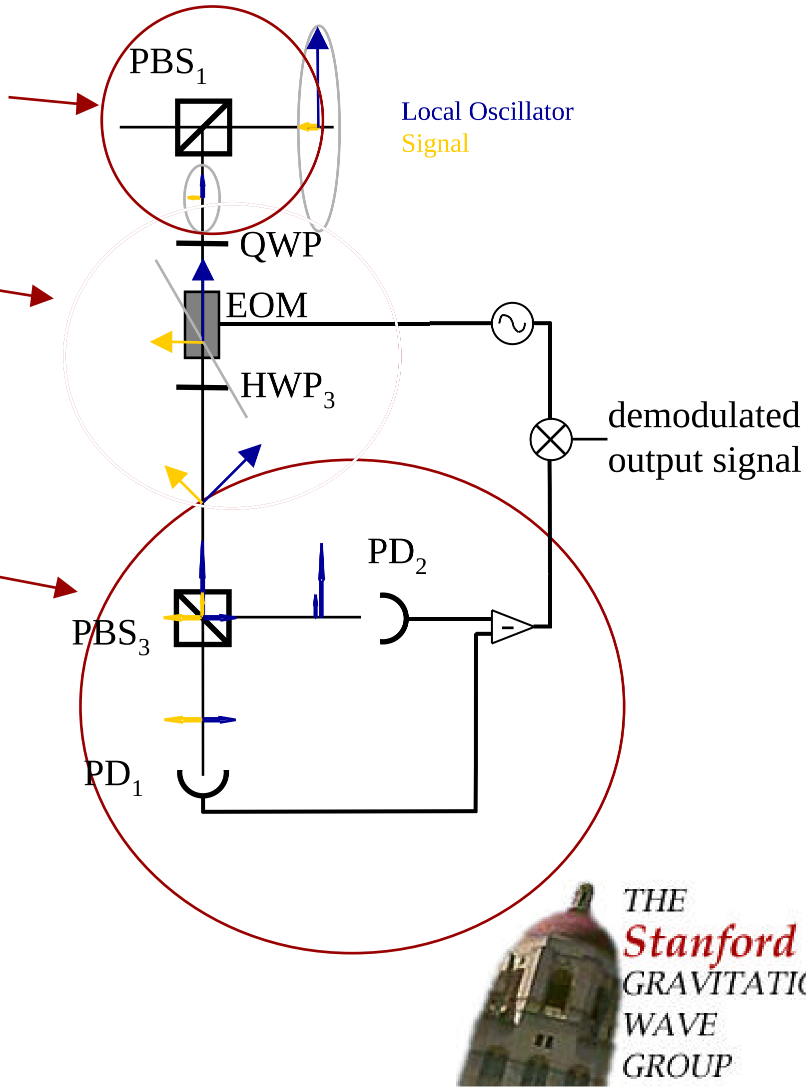
Challenges to implementing this design

- Detection of the dark fringe on the symmetric port of the beamsplitter.
- Developing a readout scheme that maintains the common path of the interfering beams.
- Reducing noise from scattered light in delay-lines.
- Handling (and generating) high circulating power
- Fabricating large mirrors for the delay lines

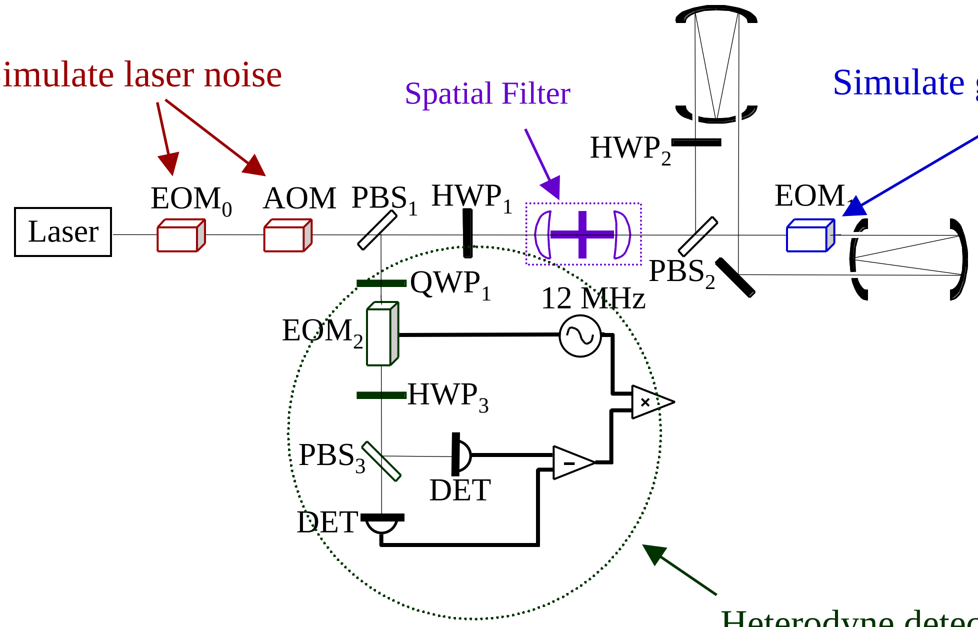
THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Signal Readout for the Polarization Sagnac

- A bit of the in-phase polarization can be leaked through the beamsplitter PBS$_1$ and used as a local oscillator.
- Alignment and relative phase control of the local oscillator to the interfering beams is not necessary since they are common path.
- Balanced detection cancels laser amplitude noise. Laser frequency noise is common to all interfering beams and does thus not effect the differential measurement.



Polarization Sagnac Experimental Set-up



Simulate laser noise

Spatial Filter

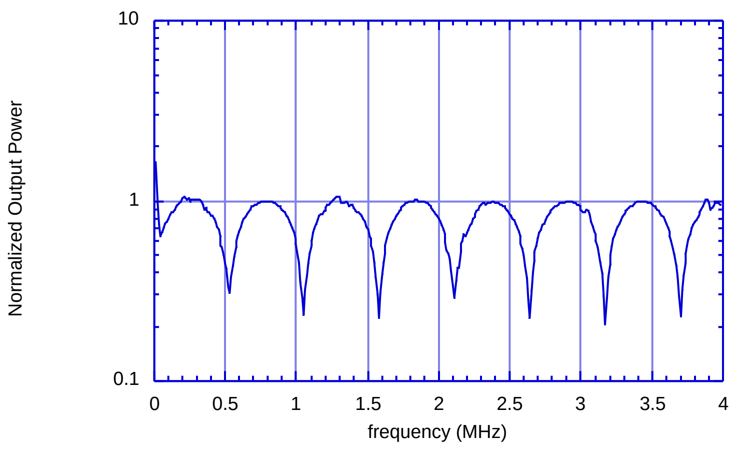
Simulate gravity wave signal

Heterodyne detection scheme

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Response of Polarization Sagnac Interferometer

Response to Gravitational Wave
is unaffected by polarization scheme



Response to laser amplitude noise
suppressed by more than 30dB
with balanced detection

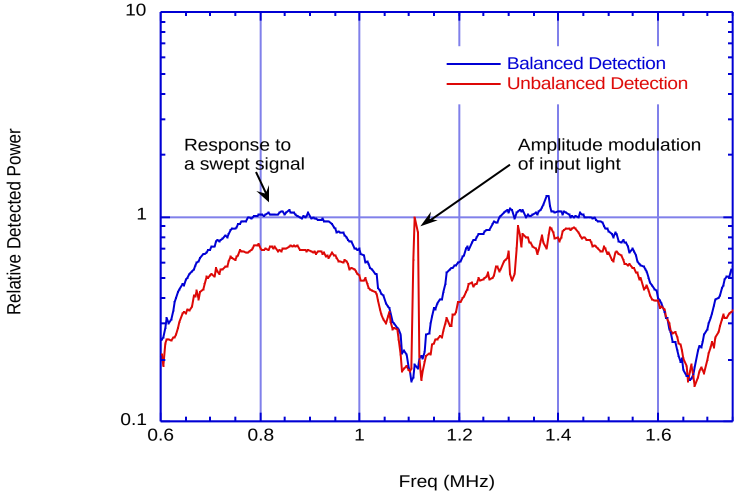
Frequency noise to amplitude noise
conversion is below 30 dB in band

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Response of Polarization Sagnac Interferometer

Response to Gravitational Wave
is unaffected by polarization scheme

Response to laser amplitude noise
supressed by more than 30dB
with balanced detection



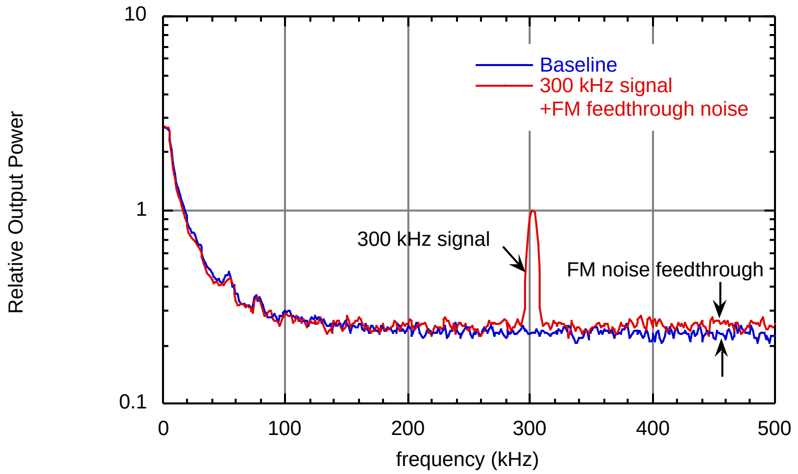
Frequency noise to amplitude noise
conversion is below 30 dB in band

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Response of Polarization Sagnac Interferometer

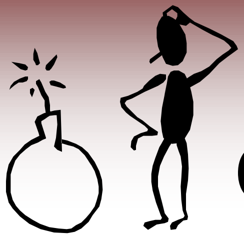
Response to Gravitational Wave
is unaffected by polarization scheme

Response to laser amplitude noise
supressed by more than 30dB
with balanced detection



Frequency noise to amplitude noise
conversion is below 30 dB in band

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

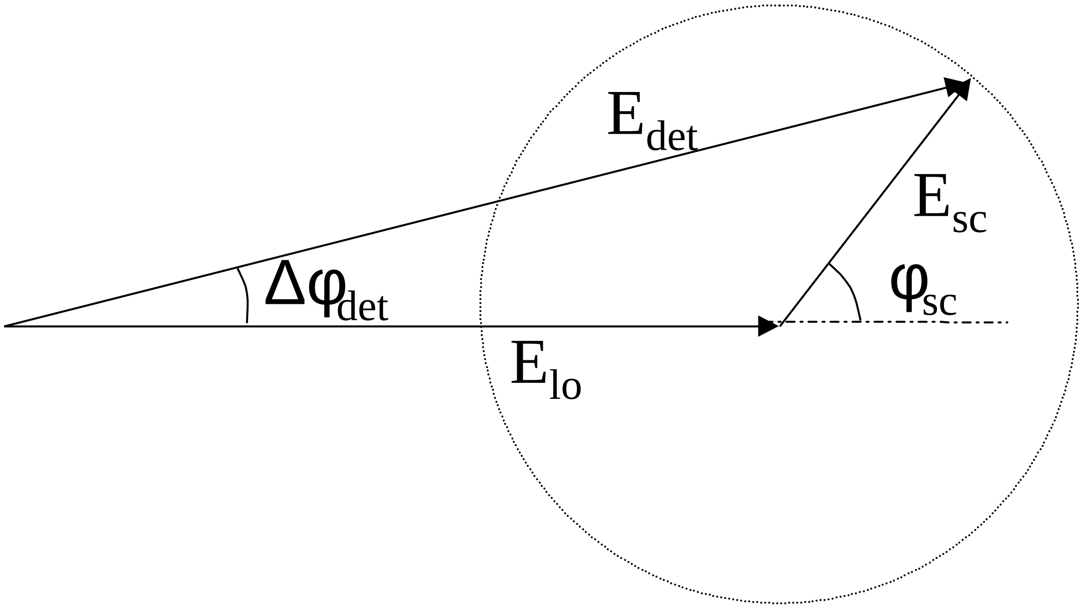


Challenges to implementing this design

- Detection of the dark fringe on the symmetric port of the beamsplitter.
- Developing a readout scheme that maintains the common path of the interfering beams.
- Reducing noise from scattered light in delay-lines.
- Handling (and generating) high circulating power
- Fabricating large mirrors for the delay lines

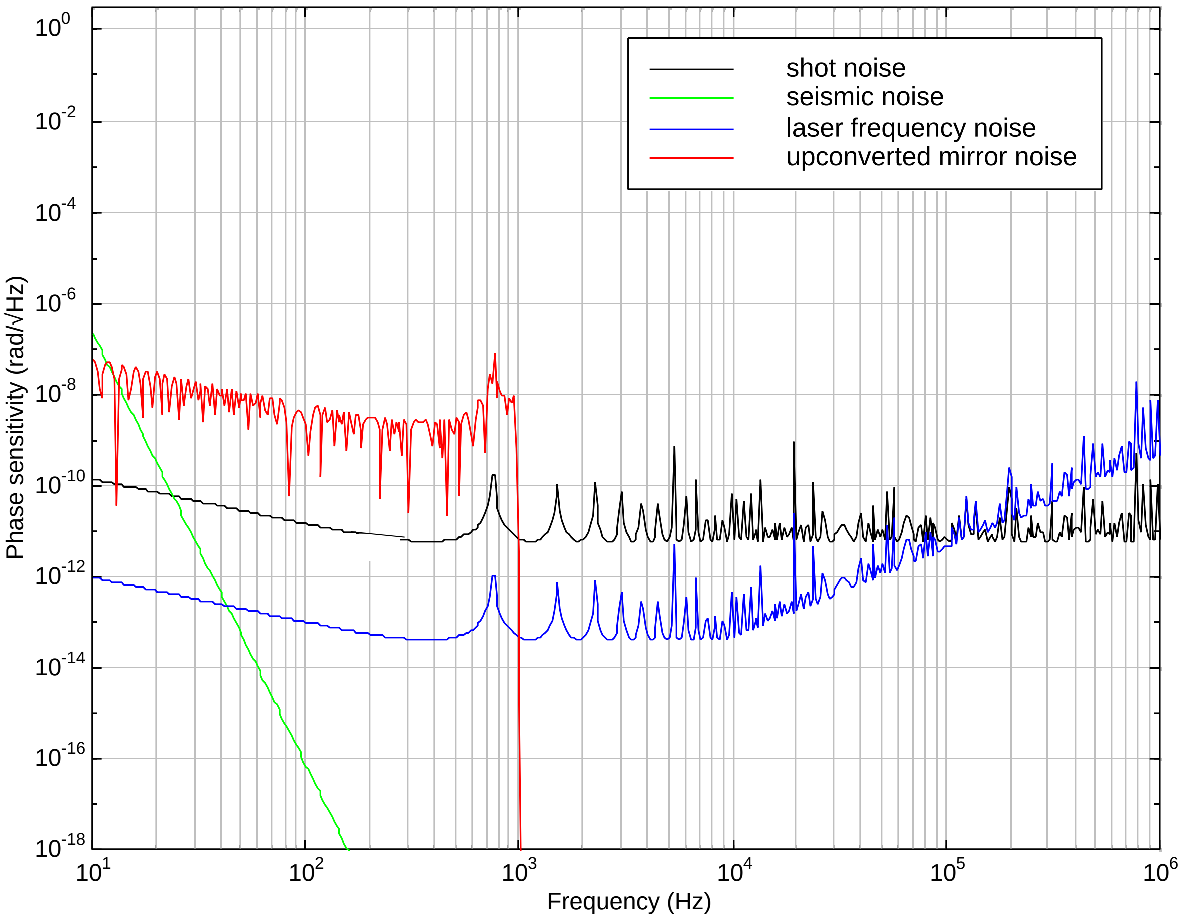
THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Effects of Scattered Light on phase noise



- It couples small in-band phase noise to noise at the detector
- It up converts large out-of-band phase noise
  to noise at the detector

Phase sensitivity with scattered light noise



Mirror Loss $=10^{-6}$
Mirror scattering $=10^{-7}$

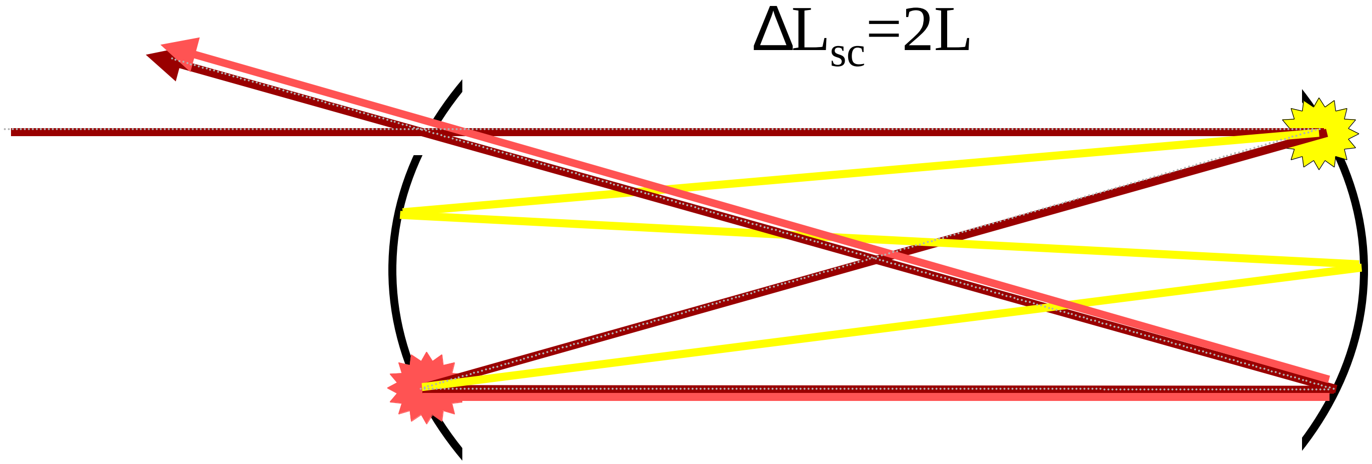
Pendulum Resonance=1Hz
Pendulum amplitude=1 mm

Length=4000 m
Delay line bounces=50

Power=10 kW
$\lambda=1.064\ 10^{-6}$ m

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Differentiating scattered light from the main beam



Scattered light will travel an integer number of extra round trips between the delay line mirrors

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Laser frequency chirp to reduce scattered light

Use large, slow modulation which is easy to produce

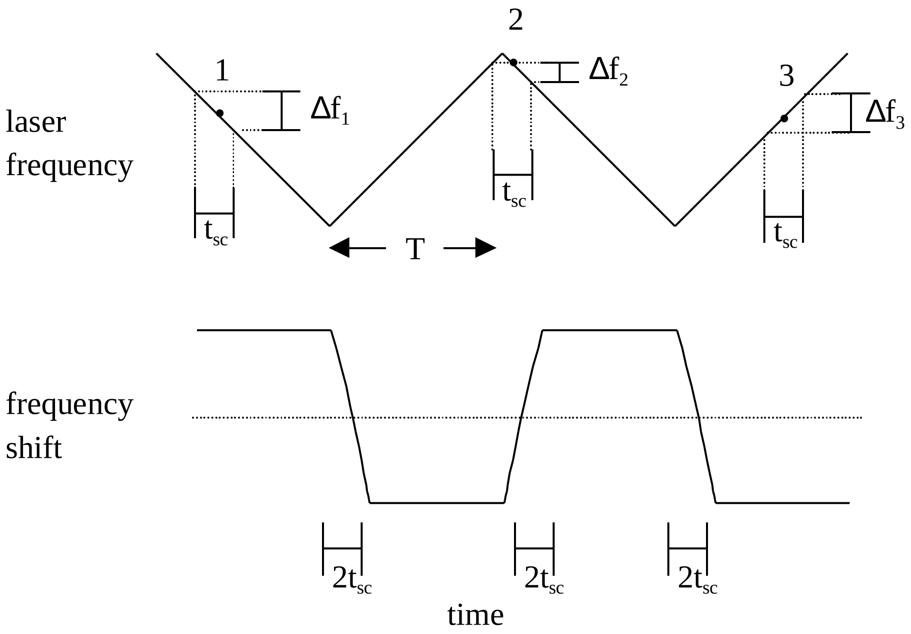
-Nd:YAG laser frequency is tunable over 50 GHz in 10 seconds by temperature tuning the crystal

The Frequency of the output light is a function of the light's transit time in the interferometer

-Scattered light will have a different frequency than the signal and local oscillator (main beam)

Scattered light will beat with the local oscillator at a frequency outside of the measurement band

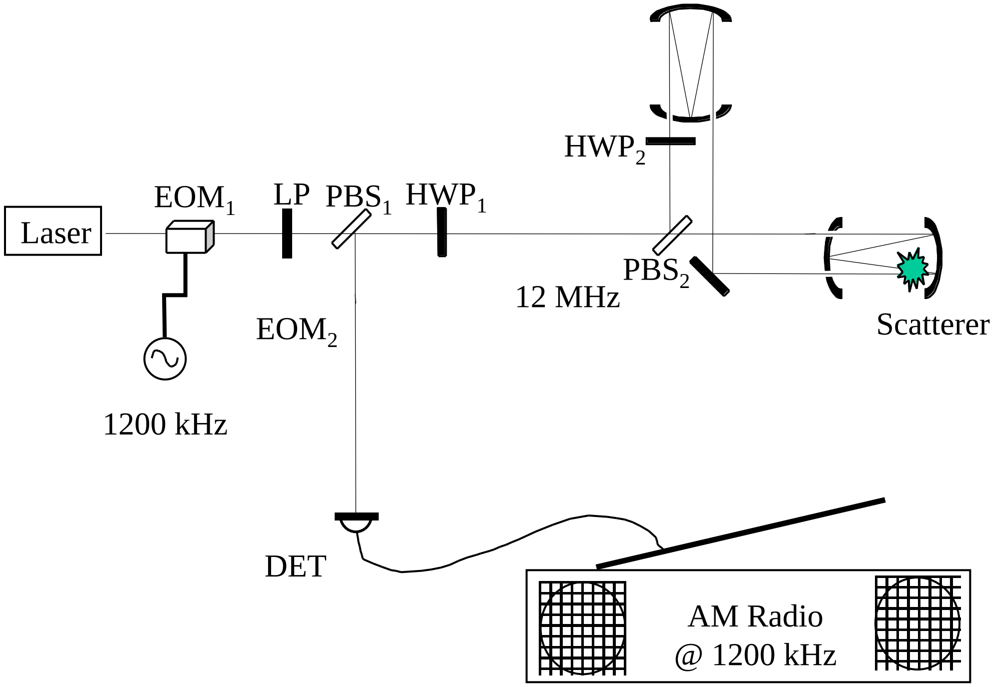
The frequency modulation waveform



Any noise from scattered light with a delay, t_{sc},
much less than the modulation period, T, will be shifted

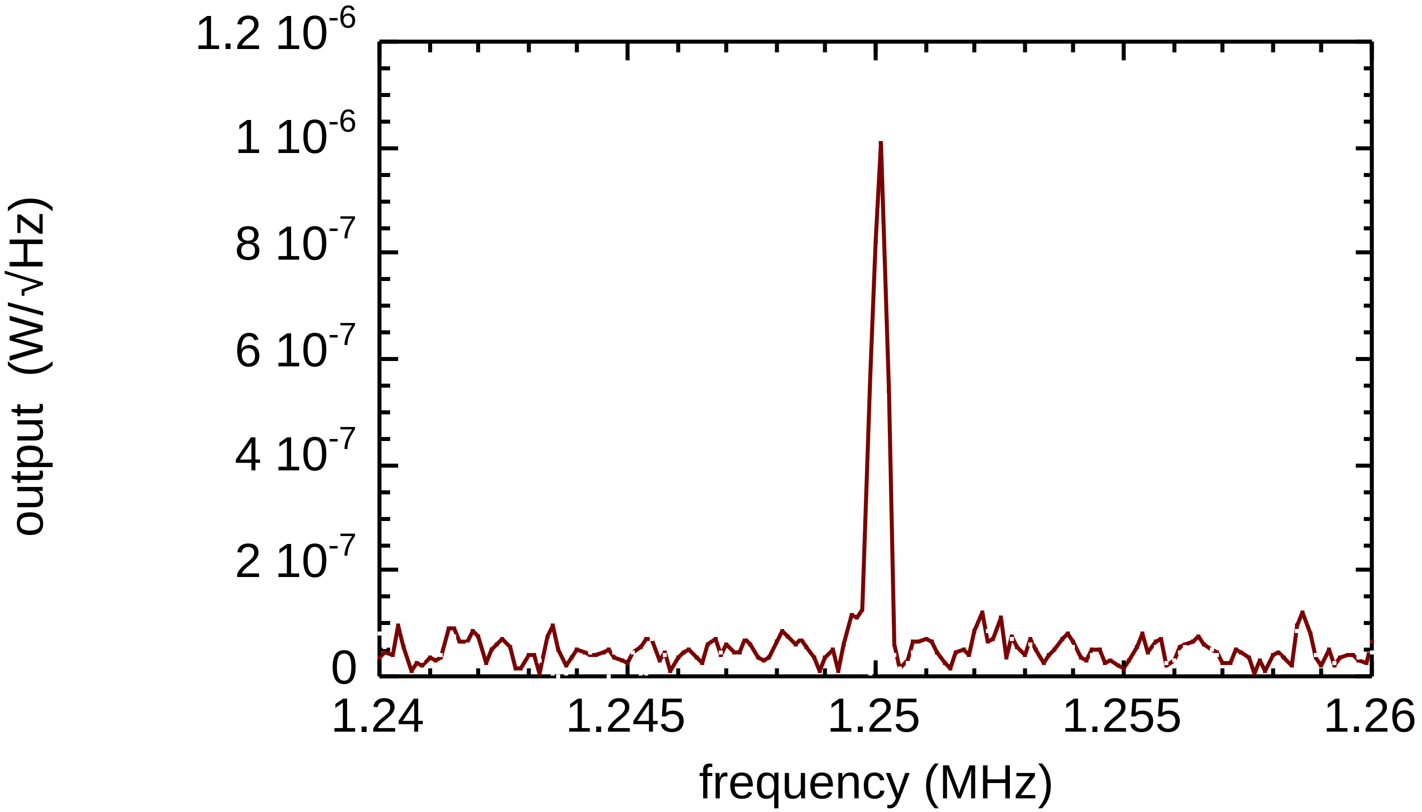
THE Stanford GRAVITATIONAL WAVE GROUP

Experimental Setup to observe scattered light noise



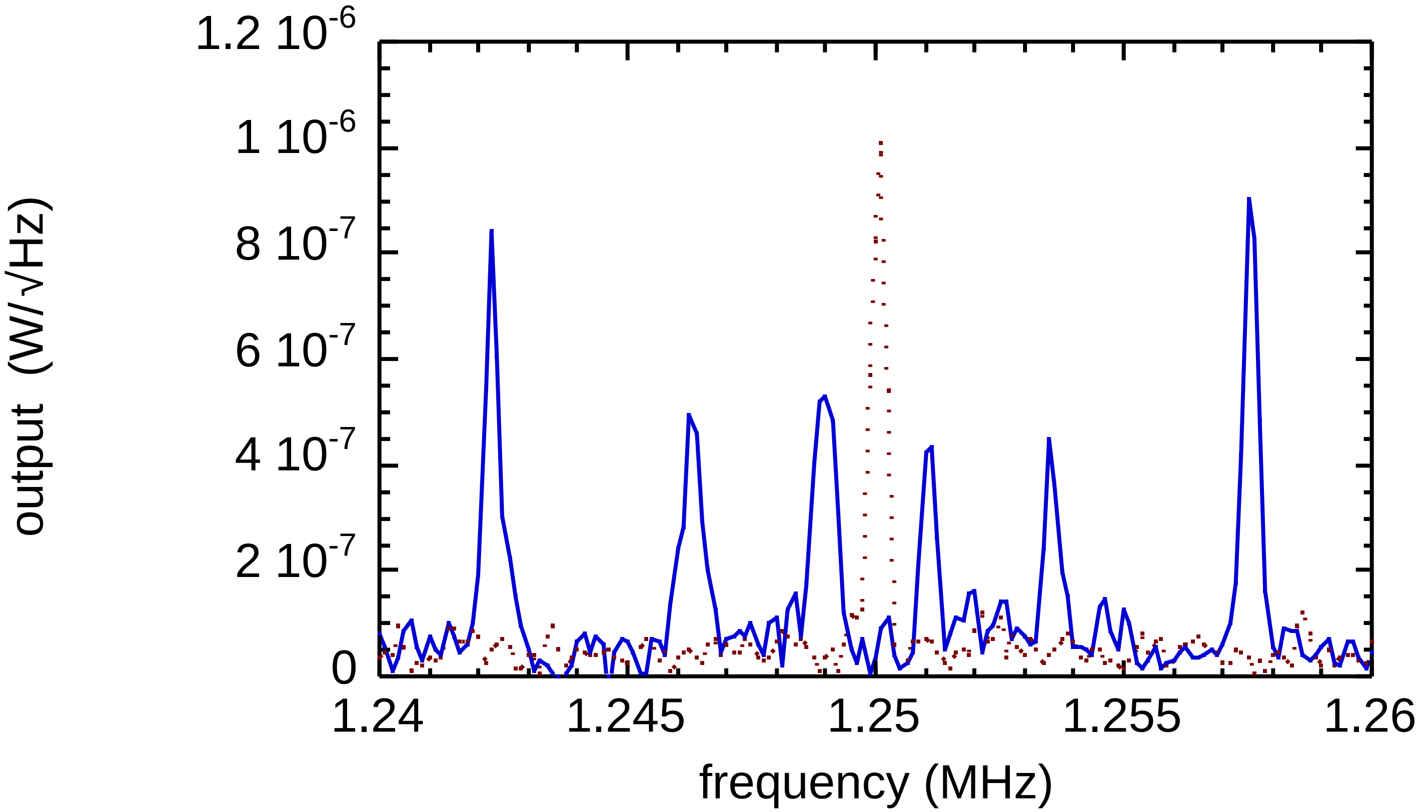
THE Stanford GRAVITATIONAL WAVE GROUP

Scattered Light Noise without Frequency Chirp



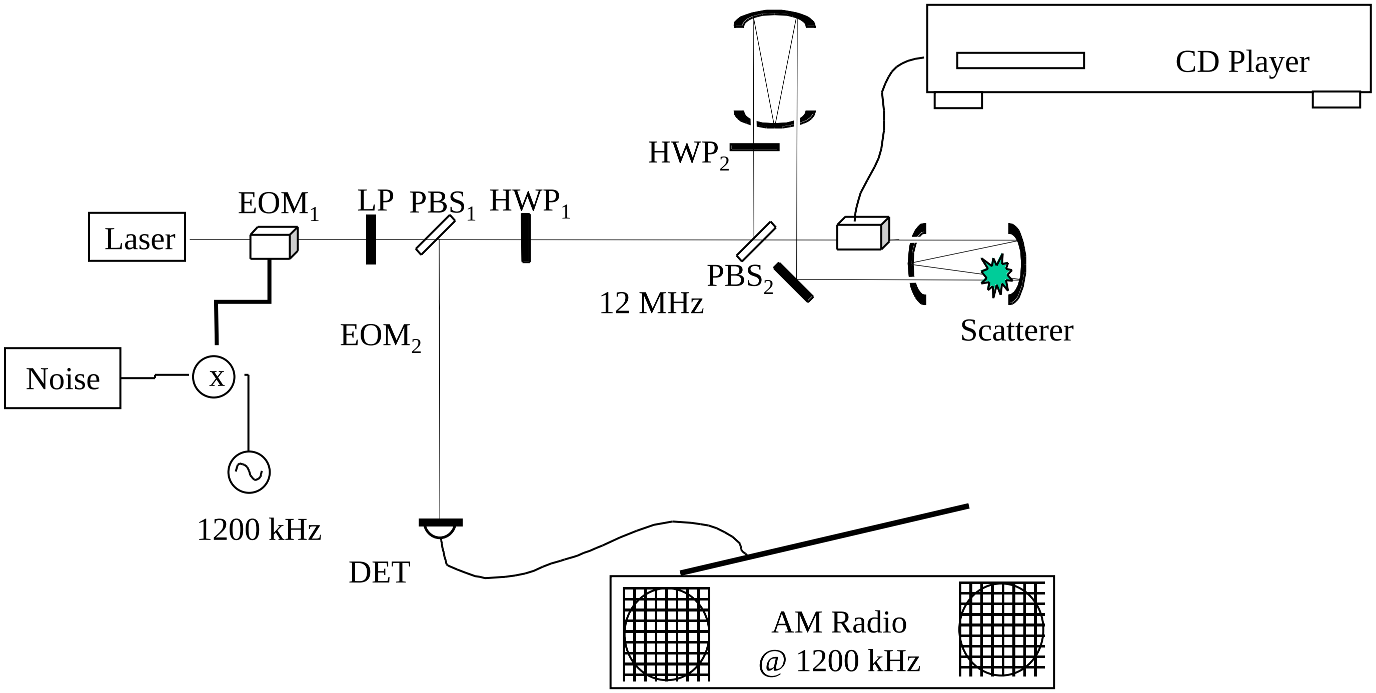
THE Stanford GRAVITATIONAL WAVE GROUP

Scattered Light Noise with Frequency Chirp



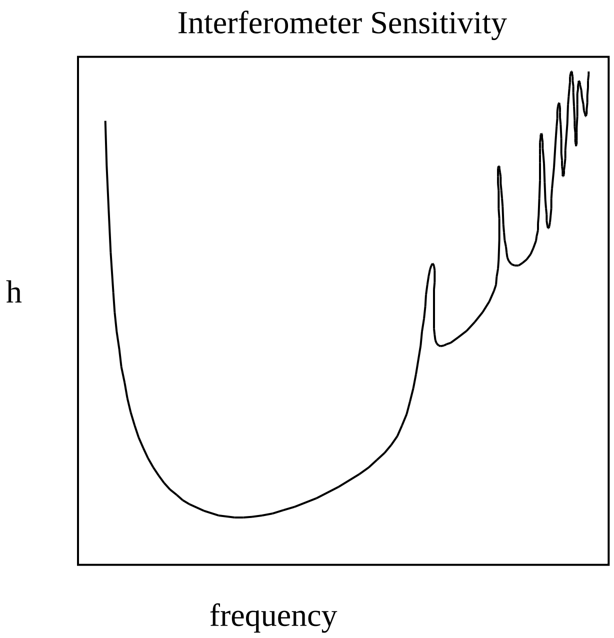
THE Stanford GRAVITATIONAL WAVE GROUP

Experimental Setup to observe effects of frequency modulation on the signal and the scattered light noise



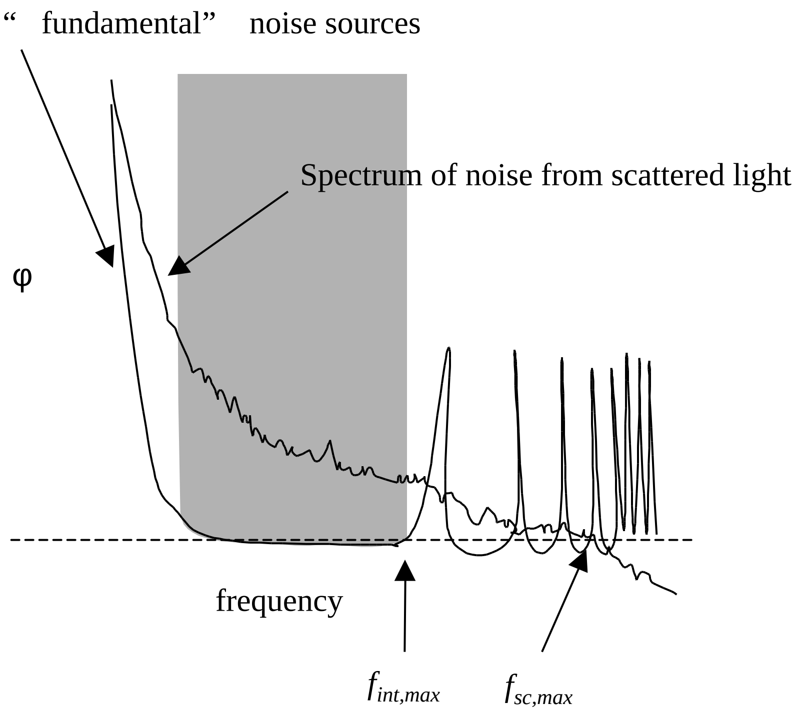
THE Stanford GRAVITATIONAL WAVE GROUP

How much does the frequency need to be shifted?



THE
Stanford
GRAVITATIONAL
WAVE
GROUP

How much does the frequency need to be shifted?



Spectrum of “ fundamental” noise sources

Spectrum of noise from scattered light

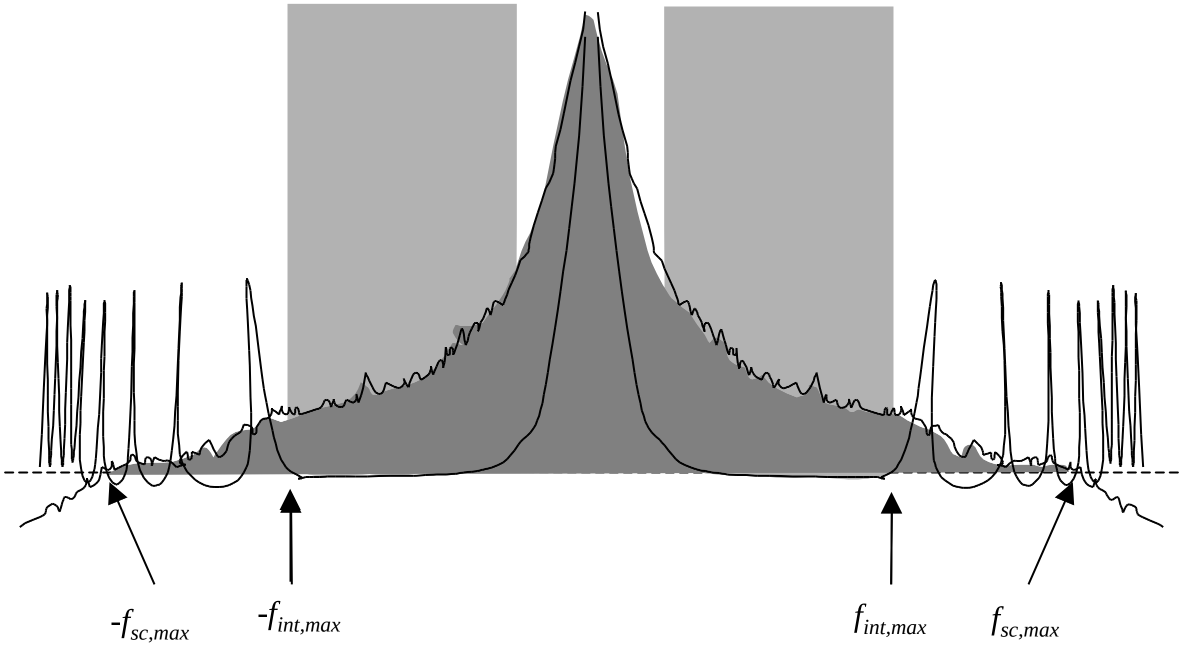
φ

frequency

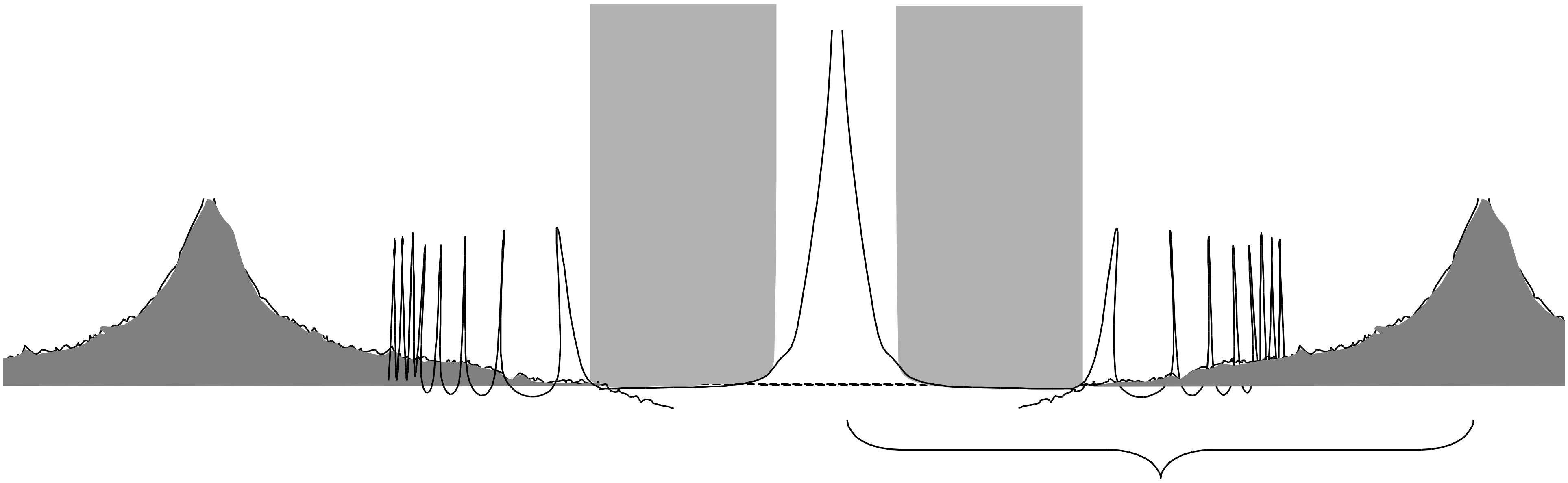
$f_{int,max}$

$f_{sc,max}$

How much does the frequency need to be shifted?



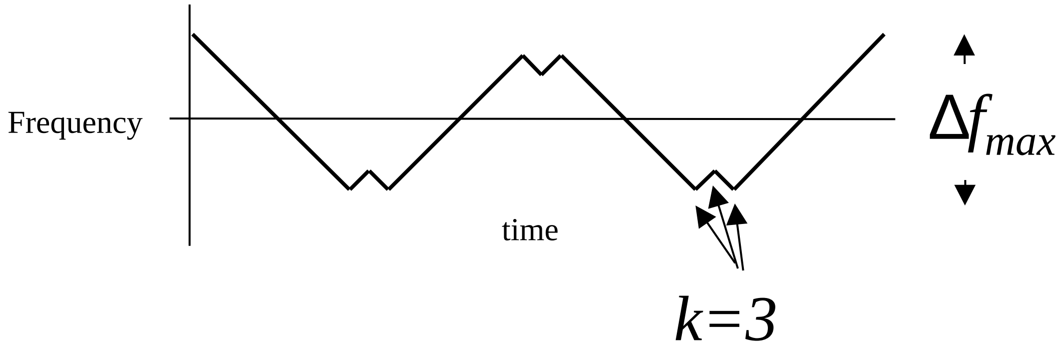
How much does the frequency need to be shifted?



$$f_{sc,max} + f_{int,max}$$

How well does frequency shifting the scattered light work?

For a laser frequency modulation waveform like

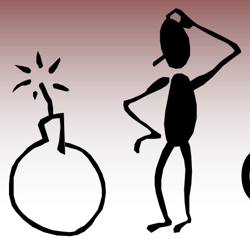


The fraction of time in which the scattered light noise can be shifted outside of the measurement band, x, is

$$x = 1 - k\,\frac{f_{sc,max} + f_{int,max}}{\Delta f_{max}}$$

For a LIGO scale interferometer, with a Lightwave 122 Master Oscillator

$$x = 1 - 5\ \ 10^{-7}$$



Challenges to implementing this design

- Detection of the dark fringe on the symmetric port of the beamsplitter.
- Developing a readout scheme that maintains the common path of the interfering beams.
- Reducing noise from scattered light in delay-lines.
- Handling (and generating) high circulating power
- Fabricating large mirrors for the delay lines

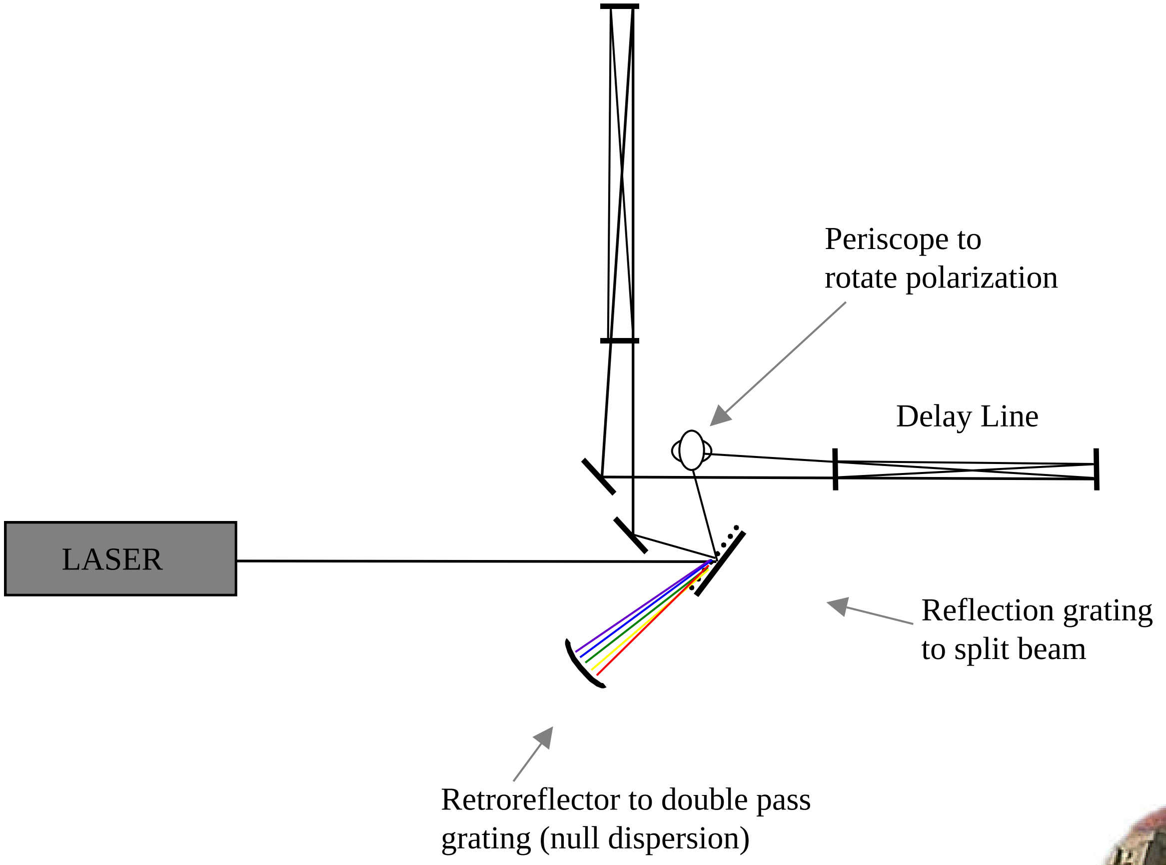
THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Handling High Power

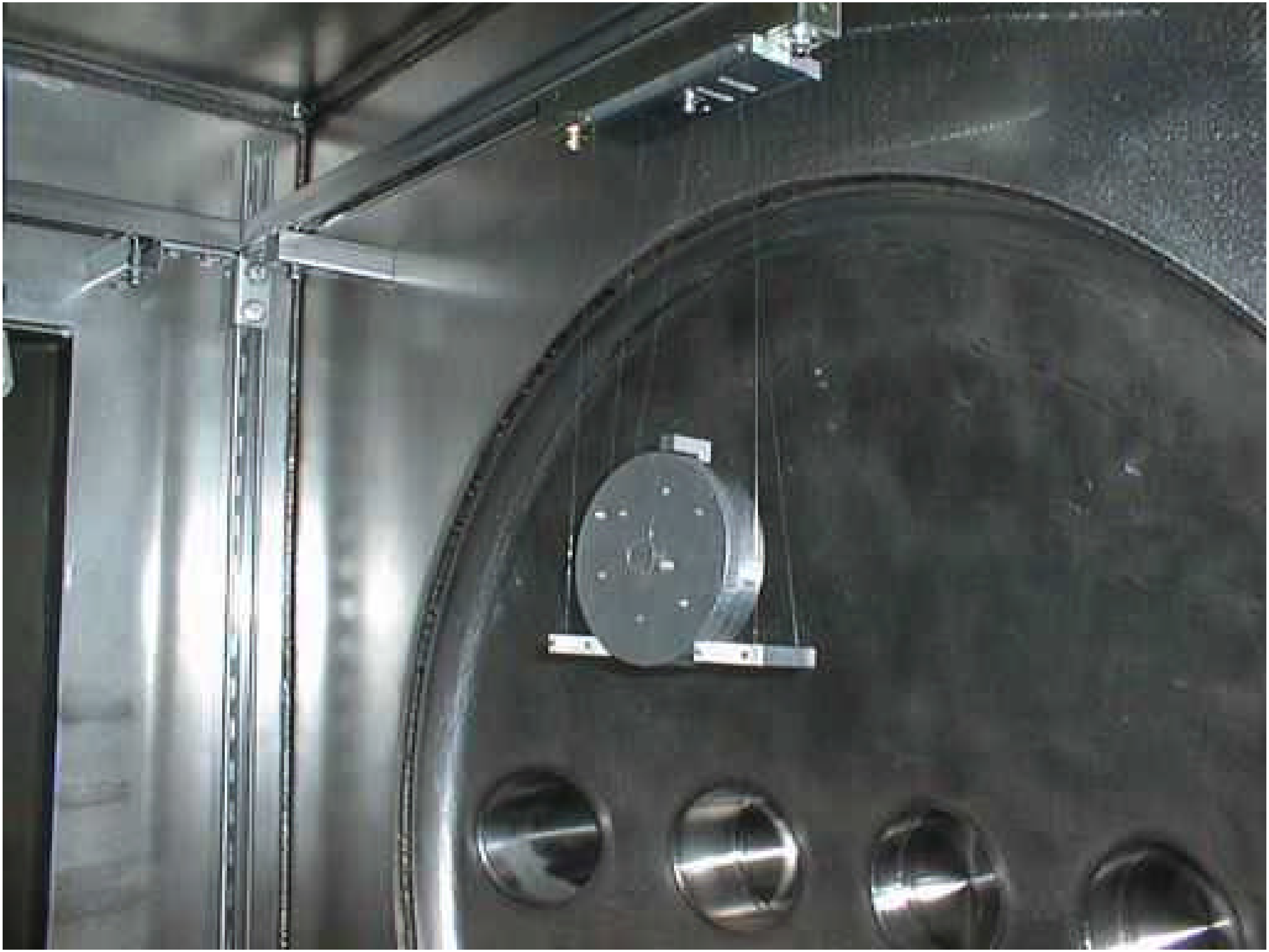
- Core optics are only used in reflection
  - No thermal lensing
  - Opaque materials can be used (Silicon)
- Phase shift from tilted mirrors can be used for polarization rotation
- Reflection grating can be used as a beamsplitter
  - Detection on the symmetrical port allows good fringe contrast with non-ideal beamsplitters
  - Double pass geometry eliminates dispersion

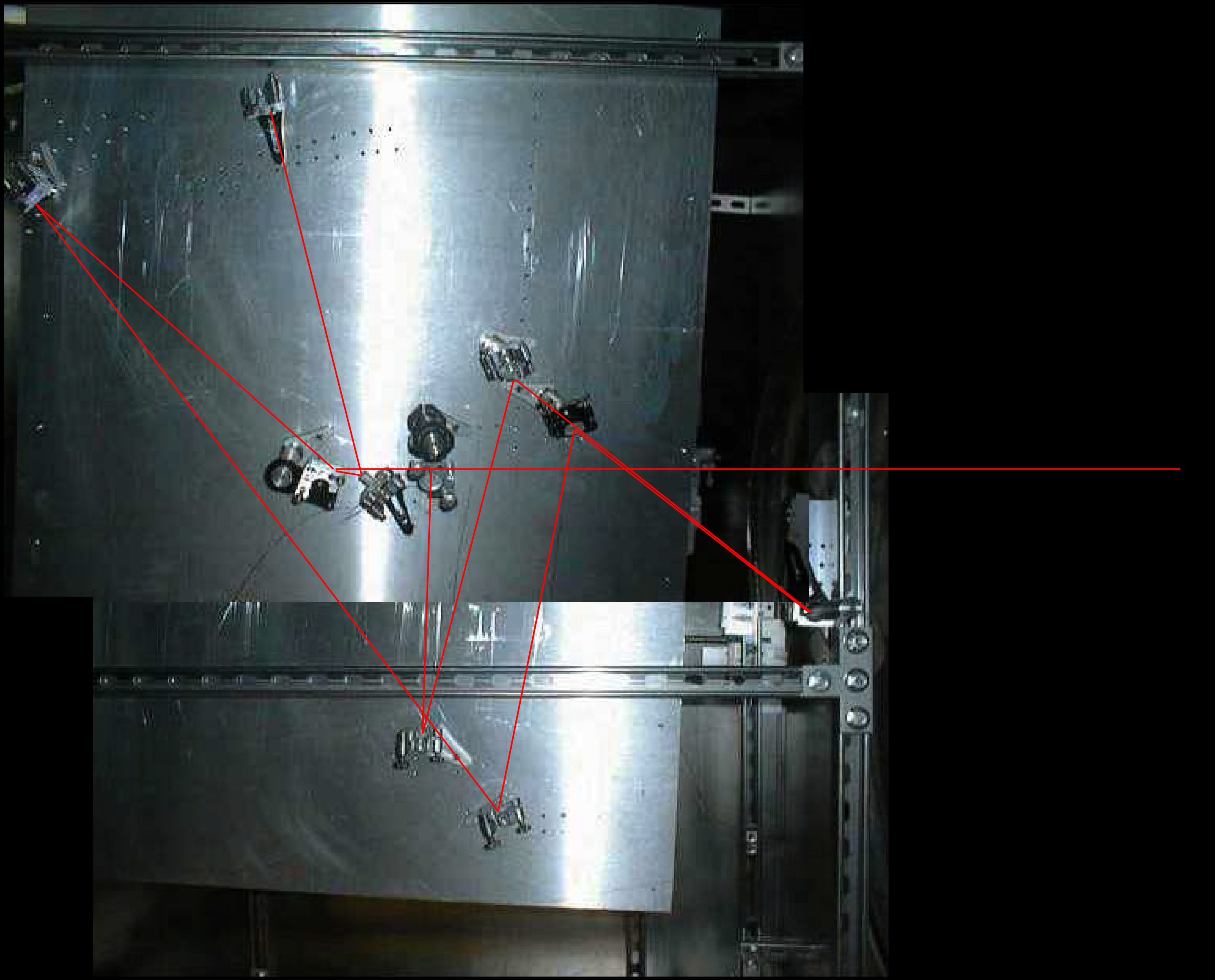
THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Layout of 10m suspended prototype all-reflective polarization Sagnac



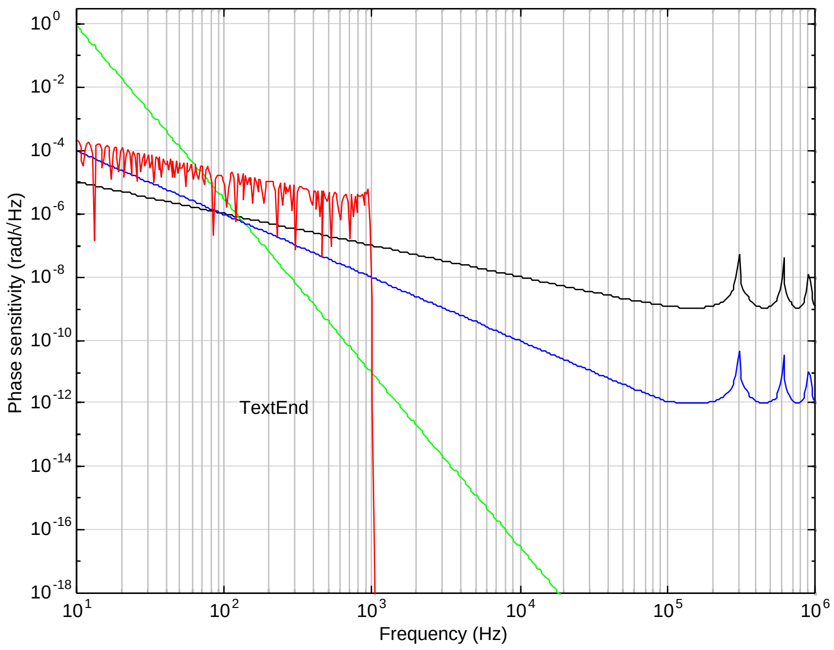
THE *Stanford* GRAVITATIONAL WAVE GROUP



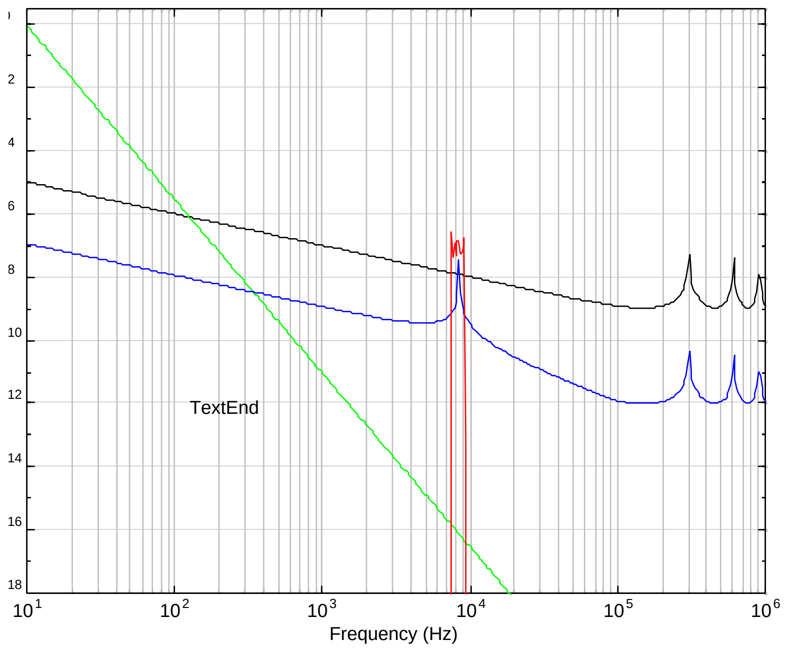


Expected Sensitivity of Prototype Sagnac

without laser frequency chirp



with laser frequency chirp



P=300mW $\quad f_o=1$

λ=1.064μm $\quad \Delta x_{max}$=1mm

— shot noise
— seismic noise
— laser frequency noise
— upconverted mirror noise

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

d/√Hz)

What more needs to be done?

- ✓ Dark fringe detection made possible on the symmetric port of the beamsplitter
- ✓ An elegant read-out scheme has been developed
- ✓ A means to suppress in-band scattered light noise has been demonstrated
- ✓ Extension of the design to an all-reflective configuration has been proposed to allow very high circulating power
- Extension of tabletop work in a suspended prototype is necessary
- A high power laser source (several kW) is necessary to illuminate the interferometer
- Large optics (~1m) are necessary for delay line mirrors

THE
Stanford
GRAVITATIONAL
WAVE
GROUP

Conclusion

- LIGO III will operate beyond the thermal limit of transmissive optics
- The Sagnac interferometer is passively controlled making it dynamically stable and suitable for high-power interferometry
- Several of the challenges of all-reflective interferometry have been met
  - polarization control allows detection at the symmetric port of the Sagnac interferometer
  - laser frequency chirp allows scattered light in delay lines to be controlled

Note 1, Linda Turner, 05/09/00 02:13:36 PM
LIGO-G000057-00-D