An Overview of Advanced LIGO Interferometry

Luca Matone

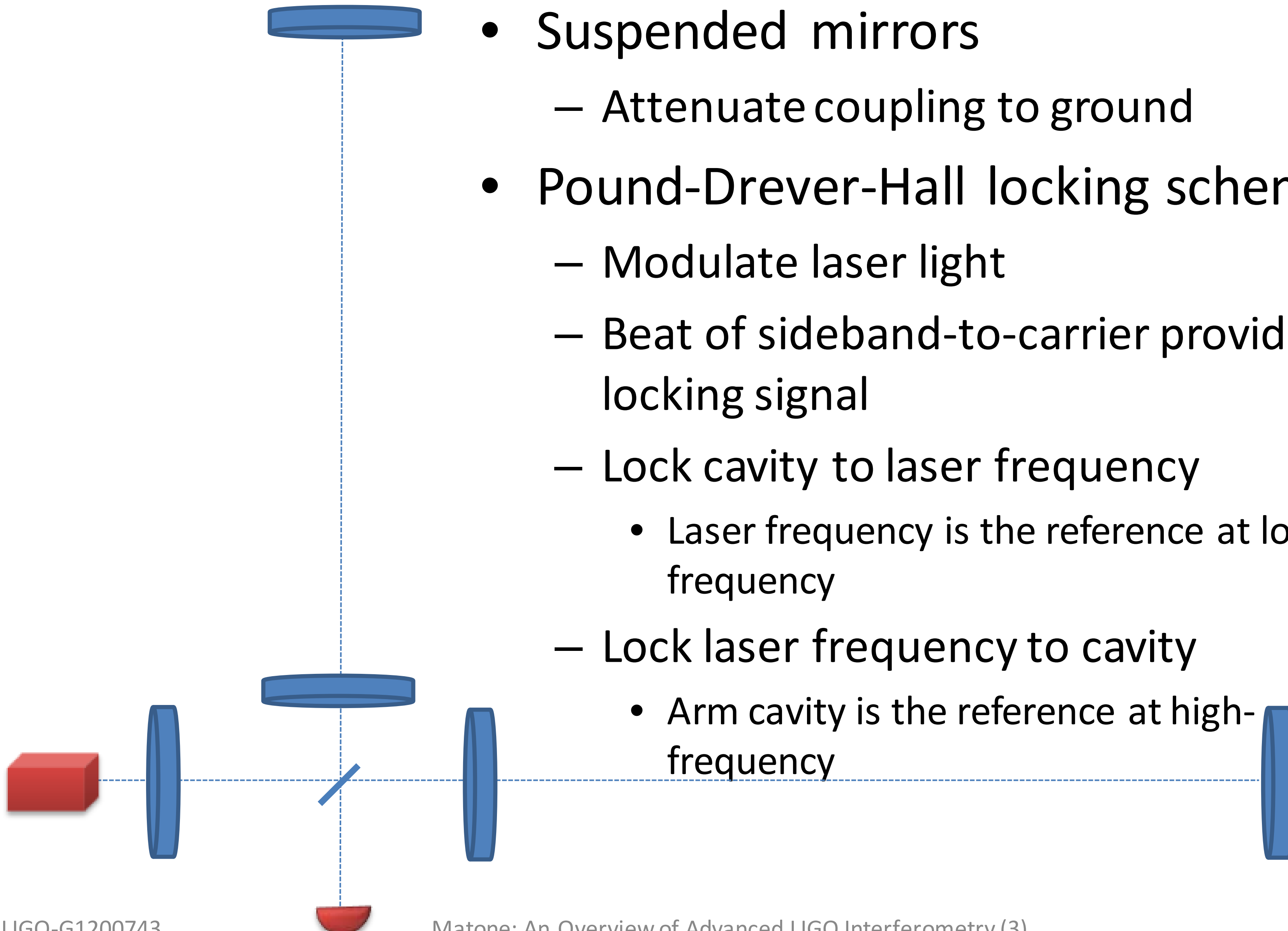
Columbia Experimental Gravity group (GECo)

Jul 16-20, 2012

LIGO-G1200743

So far…

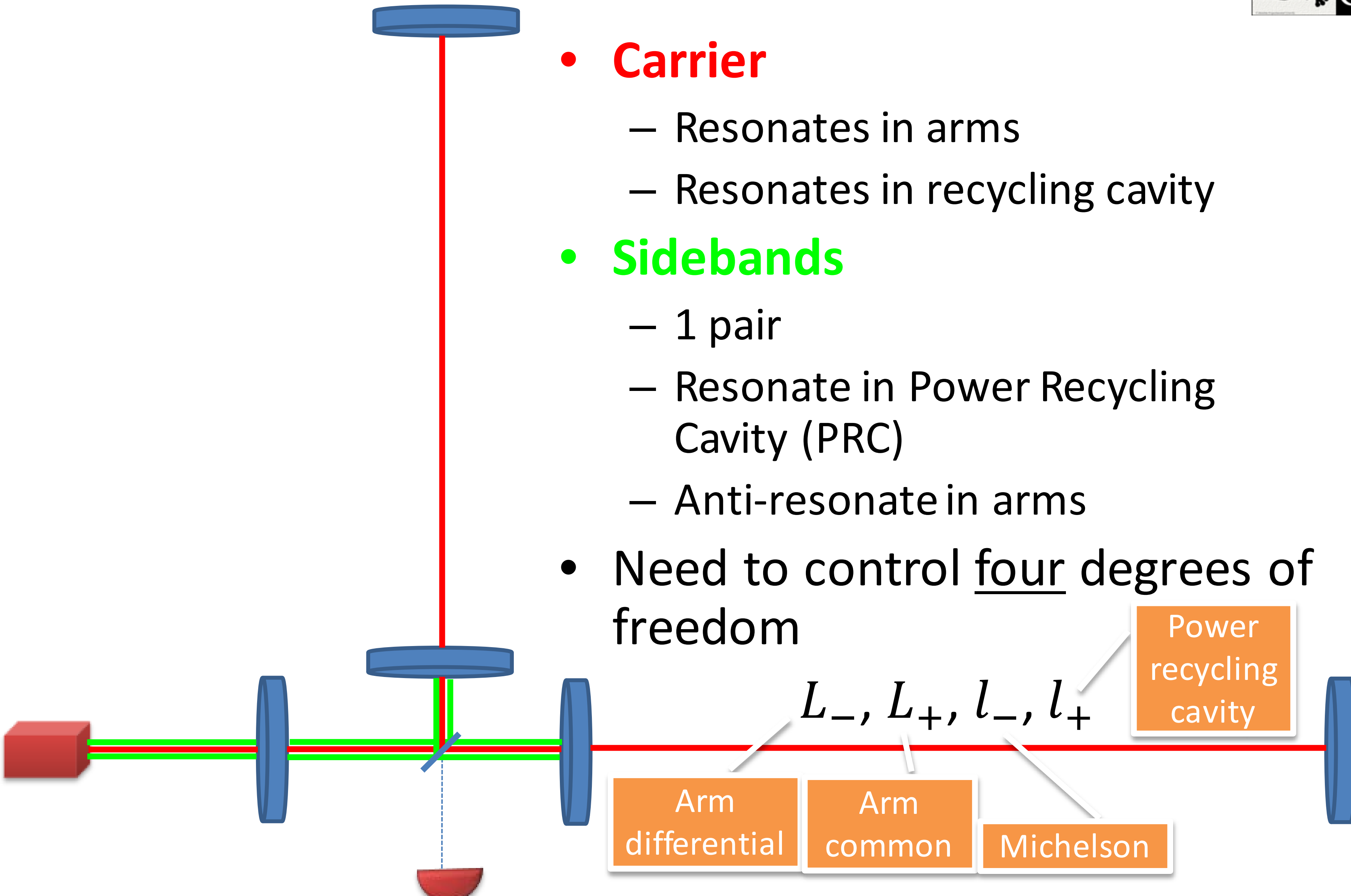
- Suspended mirrors
  - Attenuate coupling to ground
- Pound-Drever-Hall locking scheme
  - Modulate laser light
  - Beat of sideband-to-carrier provides locking signal
  - Lock cavity to laser frequency
    - Laser frequency is the reference at low frequency
  - Lock laser frequency to cavity
    - Arm cavity is the reference at high-frequency



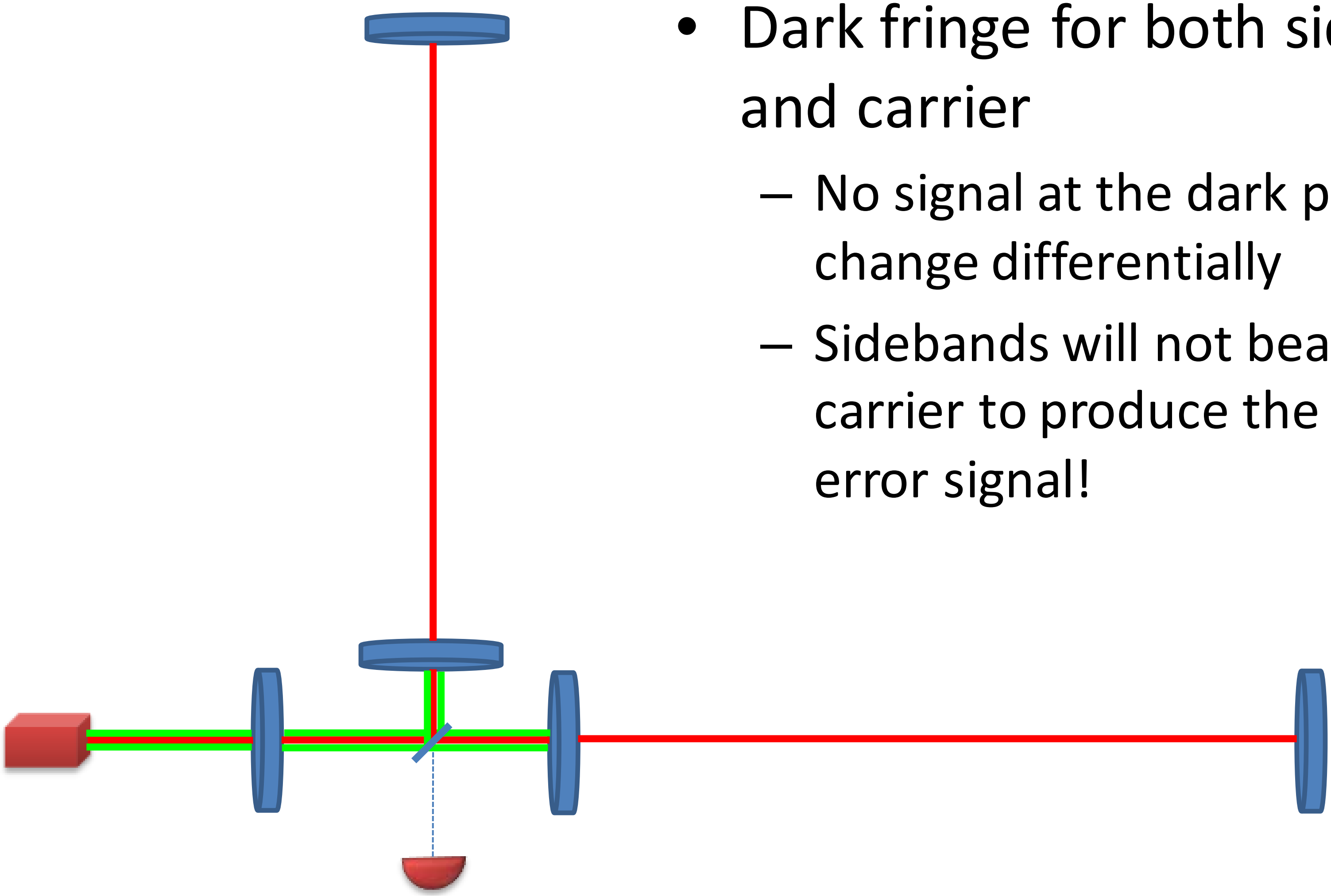
Initial LIGO Optical Configuration

- **Carrier**
  - Resonates in arms
  - Resonates in recycling cavity
- **Sidebands**
  - 1 pair
  - Resonate in Power Recycling Cavity (PRC)
  - Anti-resonate in arms
- Need to control <u>four</u> degrees of freedom

$$L_{-}, L_{+}, l_{-}, l_{+}$$

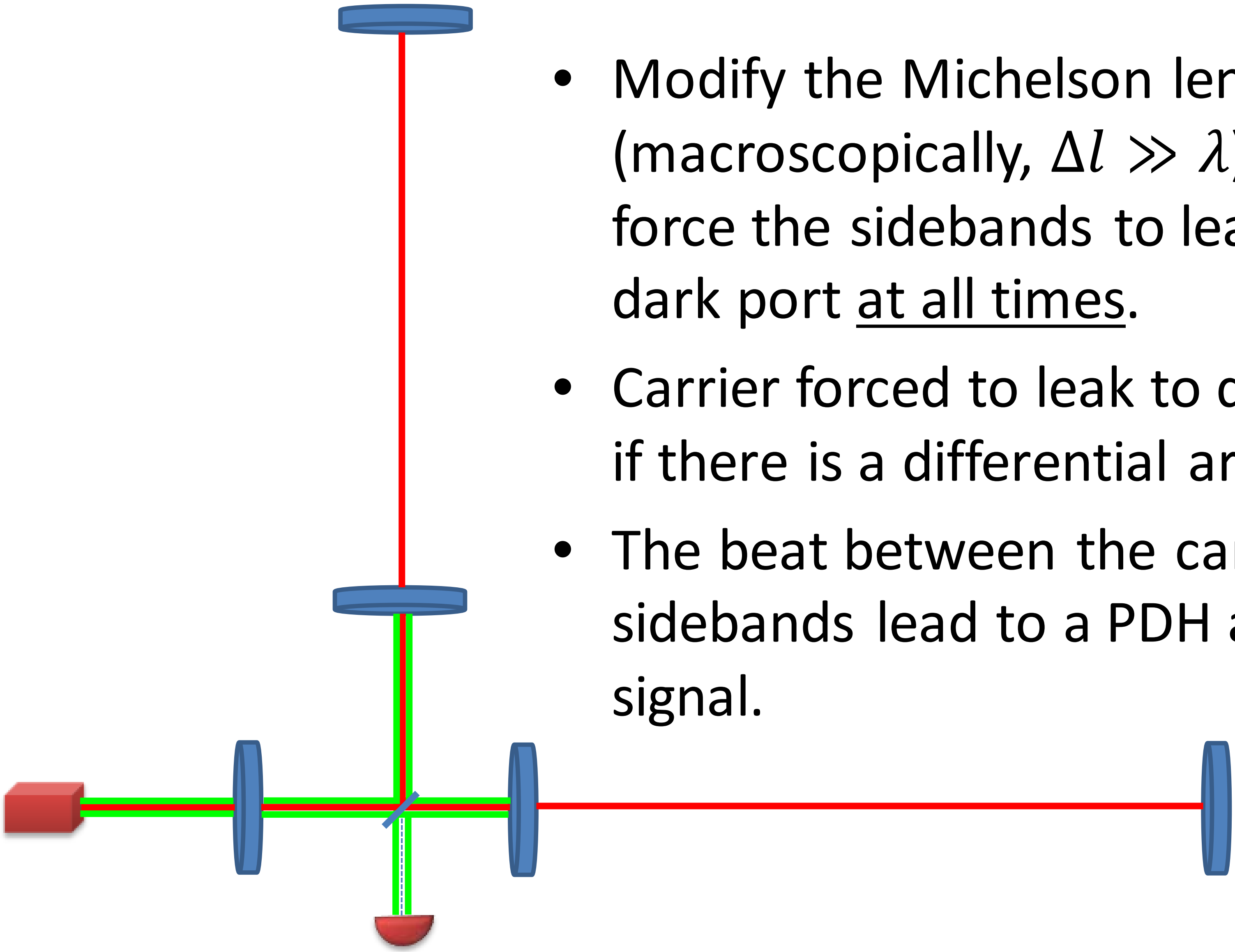


No signal yet



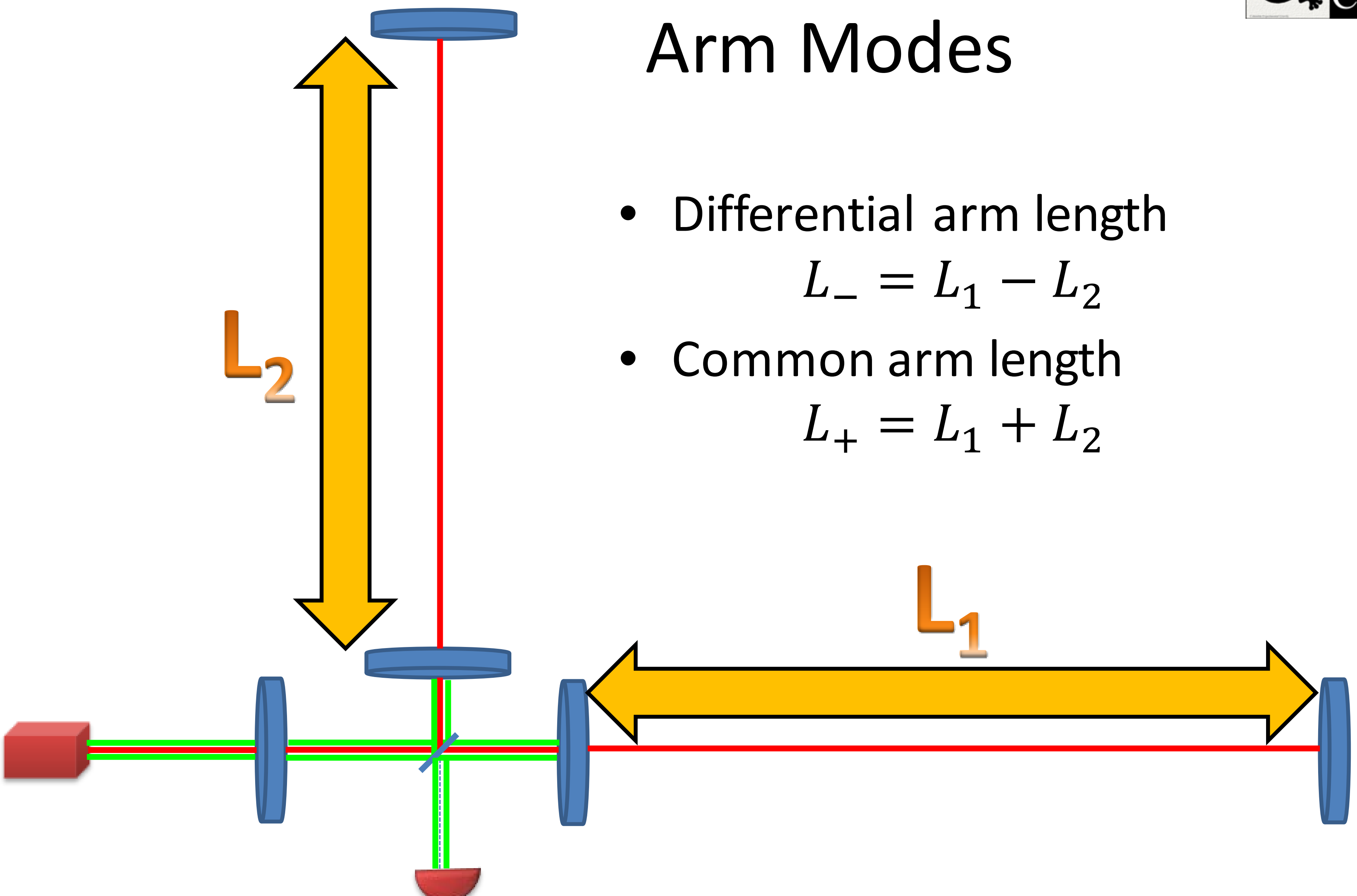
- Dark fringe for both sidebands and carrier
  - No signal at the dark port if arms change differentially
  - Sidebands will not beat against carrier to produce the dark port error signal!

Schnupp Asymmetry



- Modify the Michelson length (macroscopically, $\Delta l \gg \lambda$) so as to force the sidebands to leak to the dark port <u>at all times</u>.
- Carrier forced to leak to dark port if there is a differential arm change
- The beat between the carrier and sidebands lead to a PDH an error signal.

Common and Differential Arm Modes



- Differential arm length

$$L_- = L_1 - L_2$$

- Common arm length

$$L_+ = L_1 + L_2$$

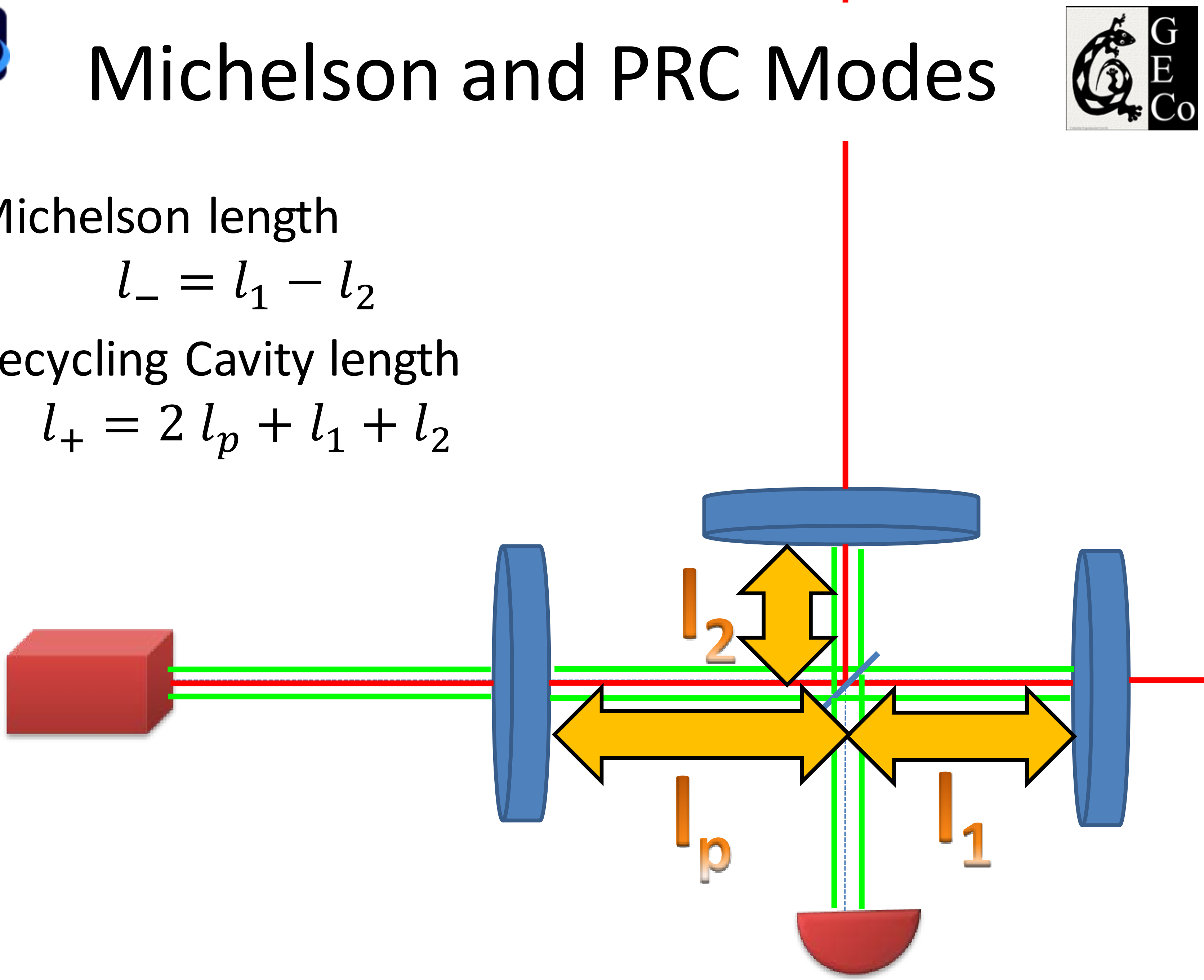
Michelson and PRC Modes

- Michelson length

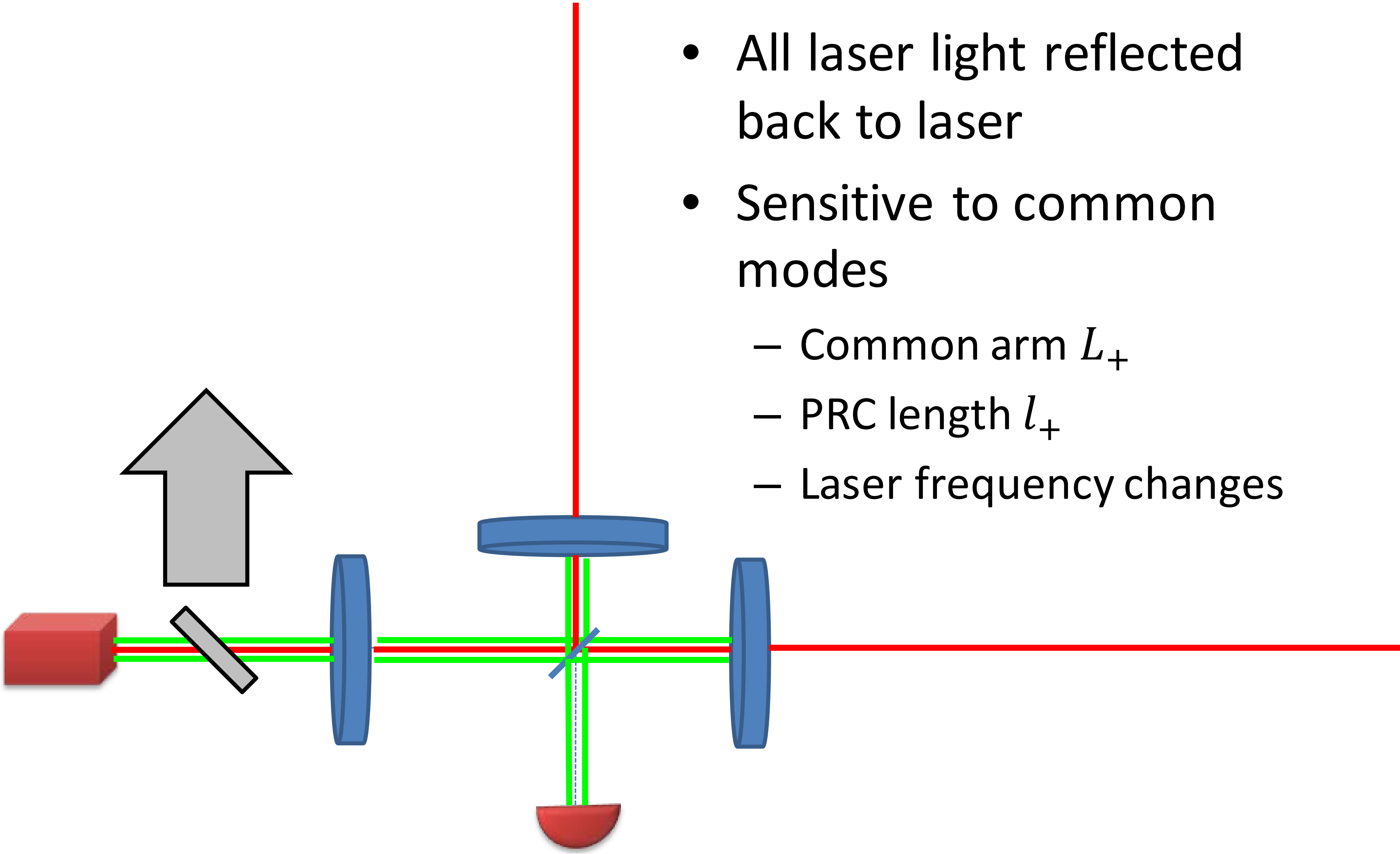
$$l_- = l_1 - l_2$$

- Recycling Cavity length

$$l_+ = 2\, l_p + l_1 + l_2$$



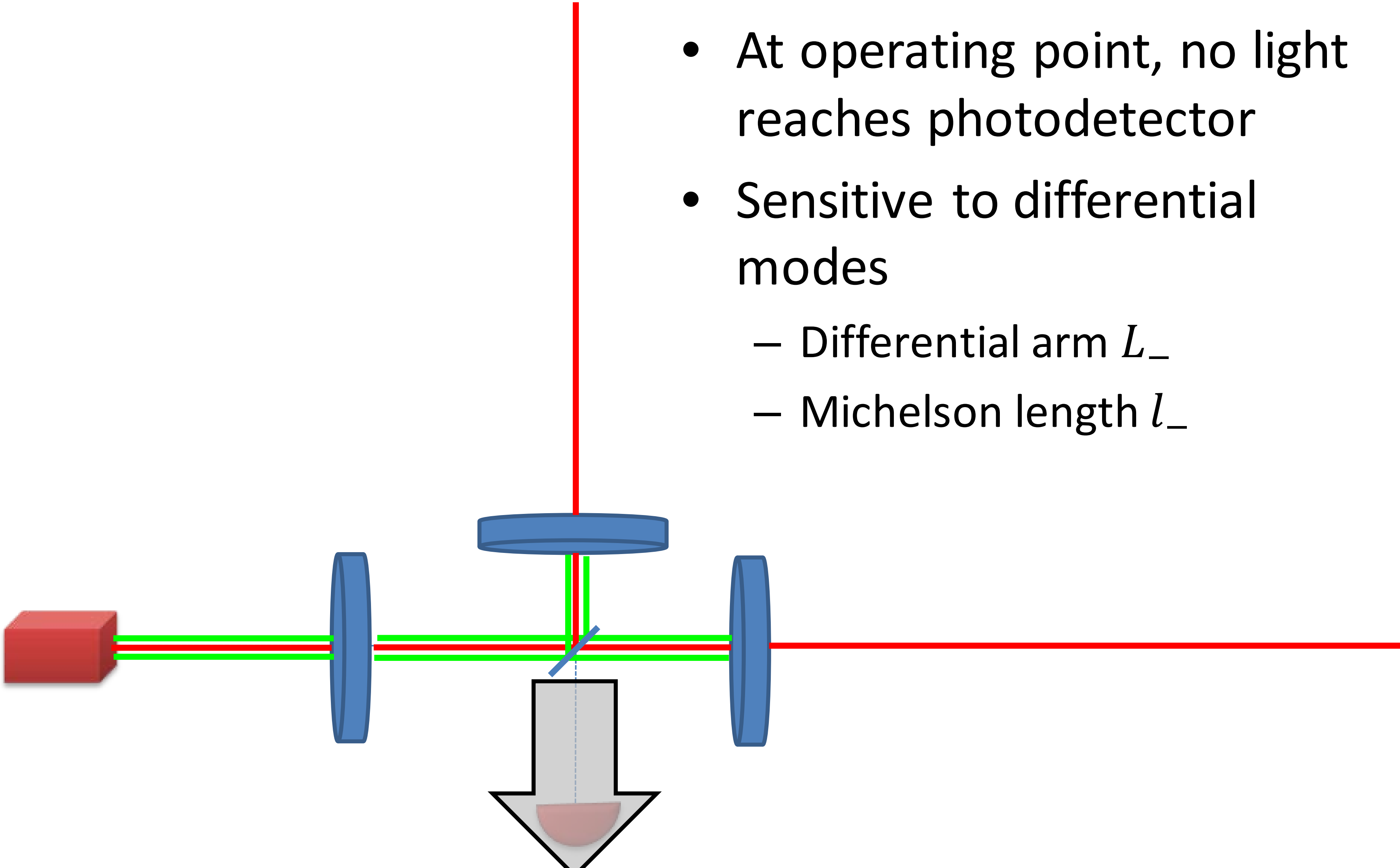
Bright Port (BP)



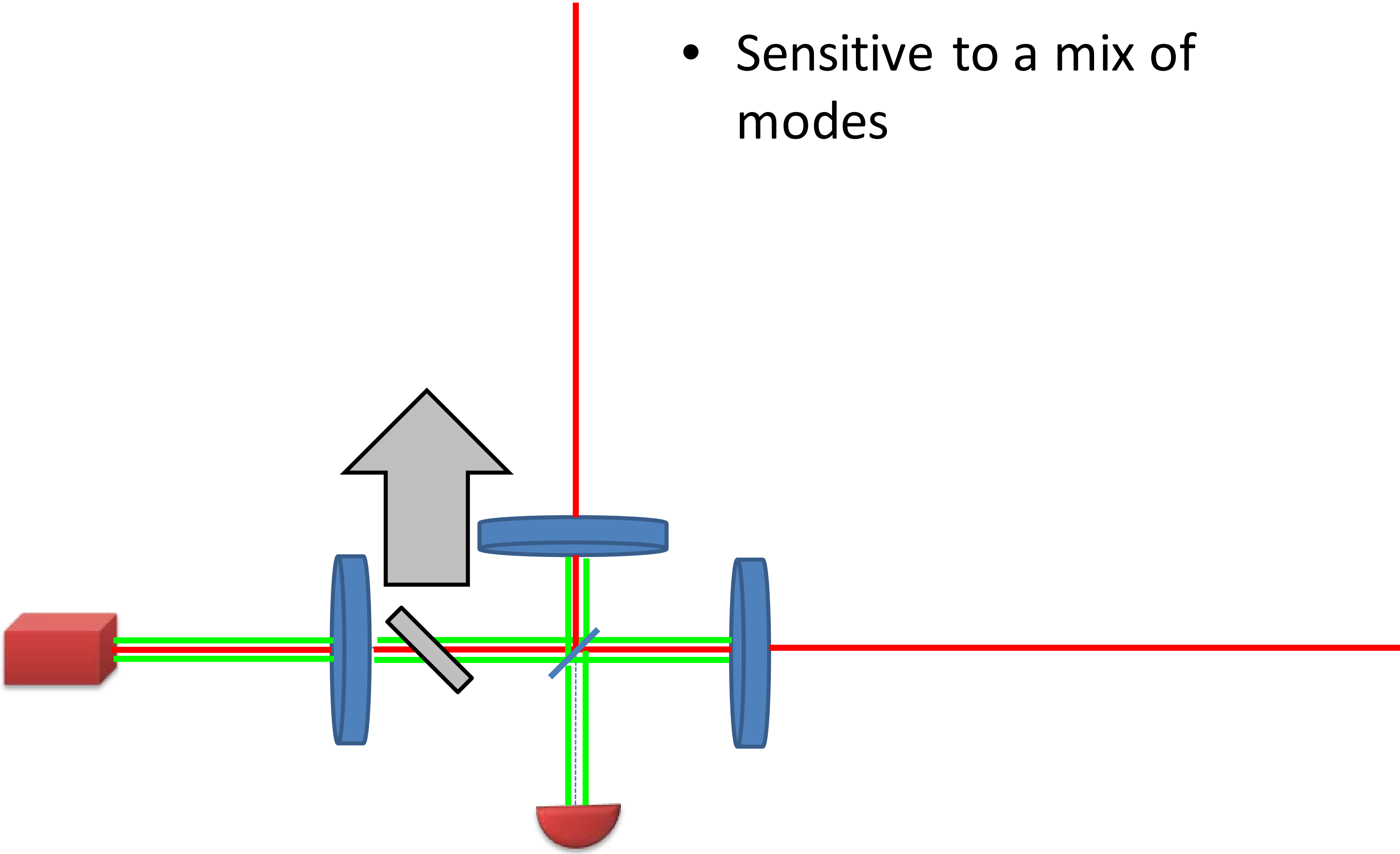
- All laser light reflected back to laser
- Sensitive to common modes
  - Common arm L_+
  - PRC length l_+
  - Laser frequency changes

Dark Port (DP)

- At operating point, no light reaches photodetector
- Sensitive to differential modes
  - Differential arm L_-
  - Michelson length l_-



Pick-off (PO)



- Sensitive to a mix of modes

Sensing Matrix

Dark Port, Quadrature

Pick off, Quadrature

Pick off, Inphase

Bright Port, Inphase

	dS_{AQ}(Volts)	dS_{PQ}(Volts)	dS_{PI}(Volts)	dS_{RI}(Volts)
dL_- (m)	$\frac{-9.6\times10^{11}}{1+s/\omega_c}$	4.72×10^{5}	0	0
dl_- (m)	$\frac{-7.3\times10^{9}}{1+s/\omega_c}$	6.20×10^{7}	0	0
dL_+ (m)	0	0	$\frac{-7.82\times10^{10}}{1+s/\omega_{cc}}$	$\frac{2.85\times10^{12}}{1+s/\omega_{cc}}$
dl_+ (m)	0	0	$\frac{-3.14\times10^{8}(1-s/\omega_p)}{1+s/\omega_{cc}}$	$\frac{-2.95\times10^{10}(1+s/\omega_r)}{1+s/\omega_{cc}}$
$d\nu_l$ (Hz)	$\frac{4.54\times10^{-12}}{1+s/\omega_c}$	0	$-\frac{1.11}{1+s/\omega_{cc}}$	$-\frac{82.8}{1+s/\omega_{cc}}$

Table 8: Interferometer Optical Plant

Laser frequency

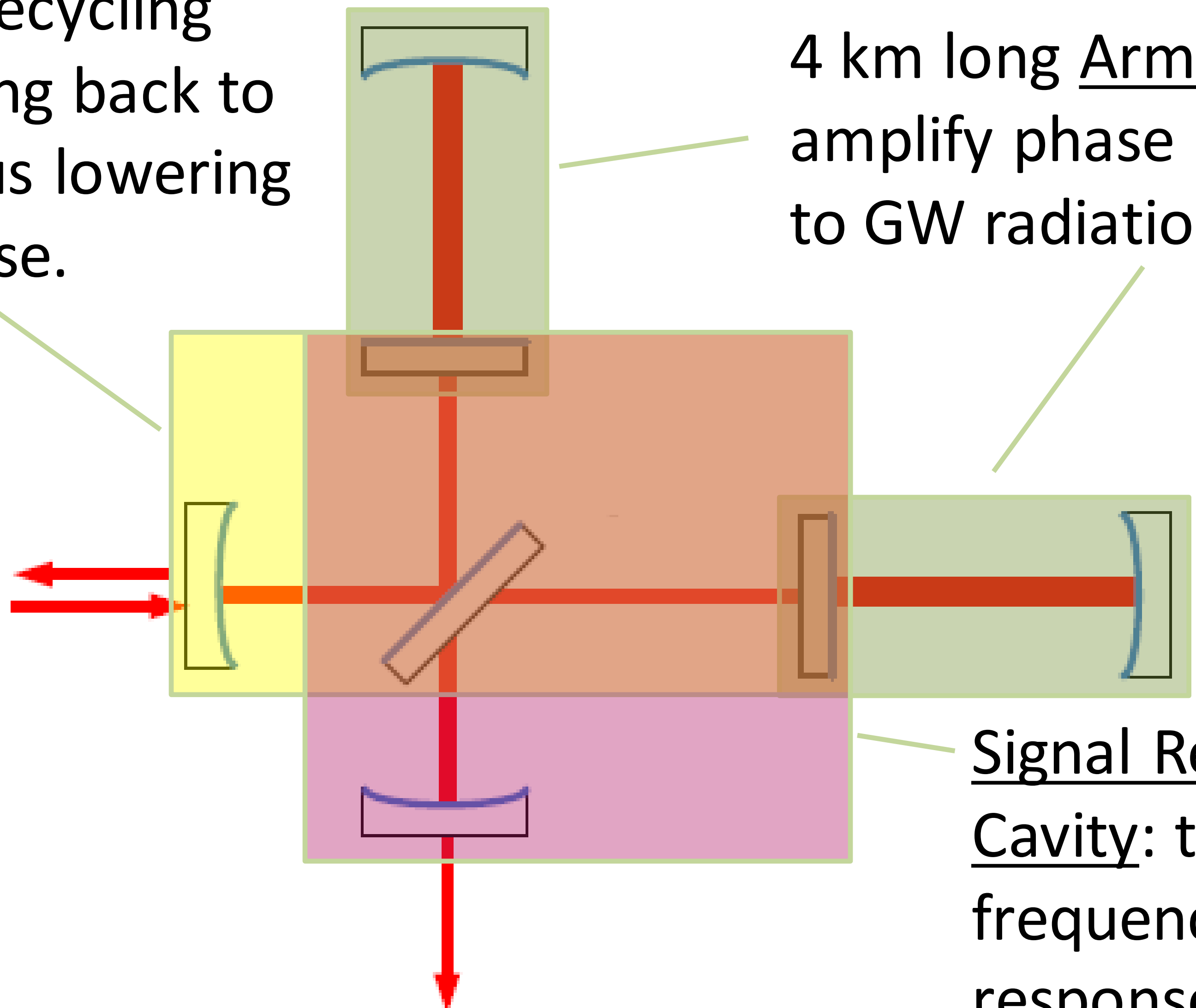
Non-diagonal

From the "Length Sensing and Control Subsystem Preliminary Design" T970122

Advanced LIGO Optical Configuration

Power Recycling Cavity: recycling light going back to laser thus lowering shot-noise.

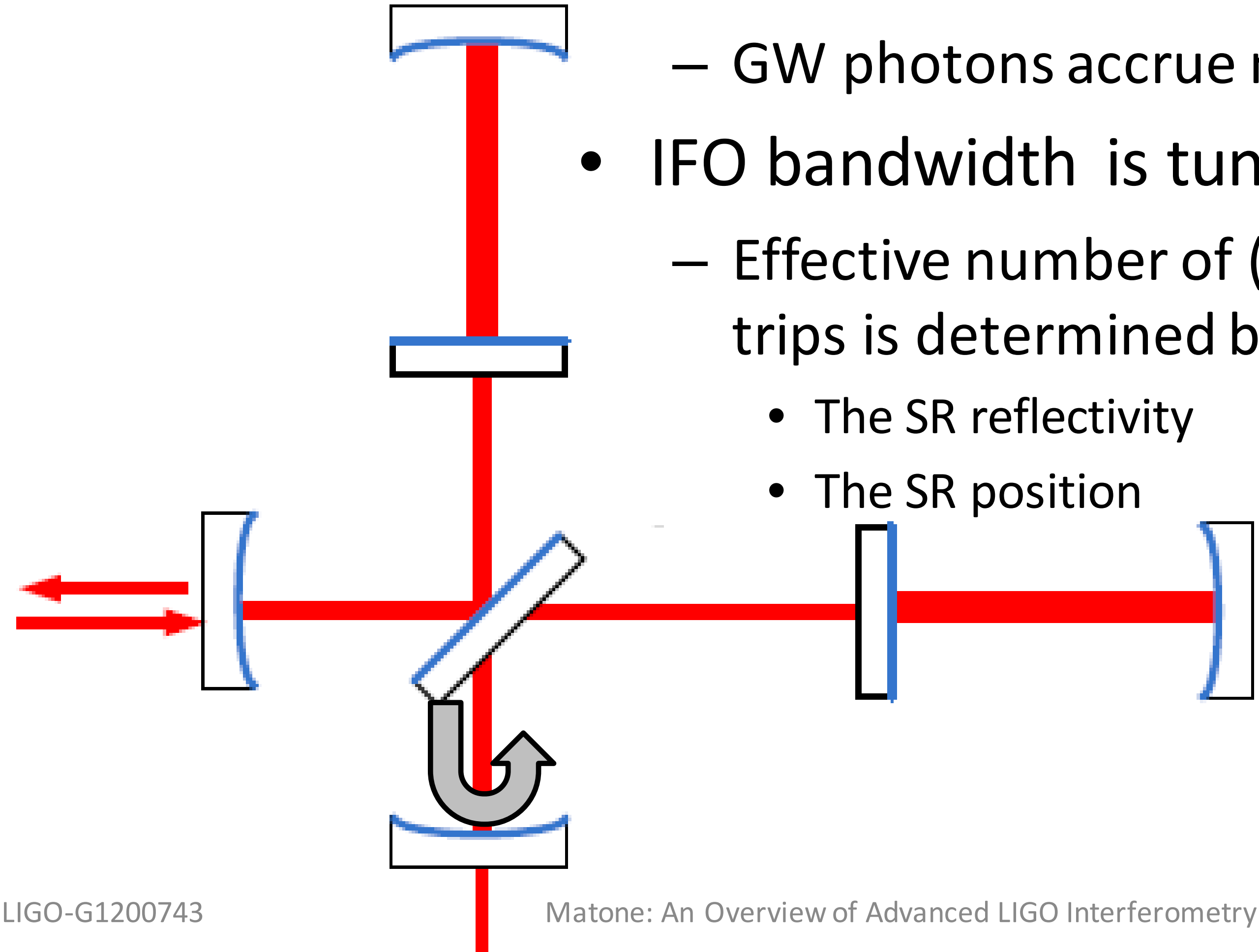
4 km long Arm Cavities: amplify phase shift due to GW radiation



Signal Recycling Cavity: tunes frequency response of IFO

Resonant Sideband Extraction (RSE)

- Signal Recycling (SR) Mirror
  - Light due to differential change is sent back to IFO
  - GW photons accrue more phase
- IFO bandwidth is tunable
  - Effective number of (GW) photon round trips is determined by
    - The SR reflectivity
    - The SR position



AdvLIGO Length Sensing and Control (LSC) Requirements

1. Bring the Advanced LIGO IFO to the desired operating point
2. Hold the IFO at the operating point
3. Provide GW signal

From "The AdvLIGO Length Sensing and Control Final Design" T1000298

Degrees of Freedom to Sense and Control

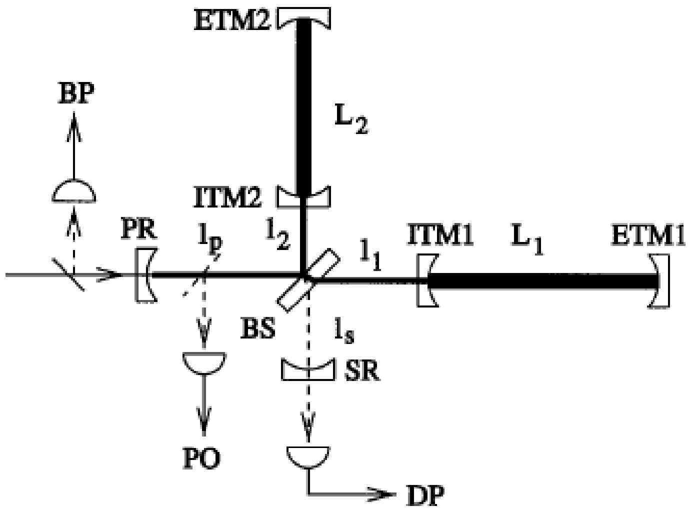


Fig. 4. Advanced LIGO interferometer consists of two arm cavities formed between the mirrors ITM1(2) and ETM1(2) of length L_1 and L_2. The distances of the arm cavities from the beam splitter (BS) are l_1 and l_2. The power-recycling (PR) mirror at a distance l_p in front of the beam splitter and the signal-recycling (SR) mirror at l_s behind the beam splitter complete the interferometer. The lengths L_i of the arm cavities are approximately 4000 m whereas the other distances are of the order of a few meters. These distances depend on the final length-sensing scheme and have to match the used modulation frequencies. Note that it is important to distinguish these macroscopic mirror spacings from the microscopic quantities that determine the phase of the light at refection from the optics. Microscopic displacements are described by their effect on the phase of the light fields. BP, bright port; DP, dark port; PO, pickoff.

Table 1. Five Relevant Longitudinal Degrees of Freedom in an Advanced LIGO Interferometer[a]

Description	Symbol	Physical Distance
Differential arm cavity	Φ_-	$2k\,(L_1 - L_2)$
Common arm cavity	Φ_+	$2k\,(L_1 + L_2)$
Differential Michelson	ϕ_-	$k\,(l_1 - l_2)$
Power-recycling cavity	ϕ_+	$k\,(2l_p + l_1 + l_2)$
Signal-recycling cavity	ϕ_s	$k\,(2l_s + l_1 + l_2)$

[a]It is convenient to describe the two arm cavities by use of their average or common length and their length difference or differential length instead of the individual lengths. The $k = 2\pi/\lambda$ is the wave number. Note that the phases given under the symbol column correspond to microscopic changes of the macroscopic lengths given in the physical distance column.

Five degrees of freedom

From K. A. Strain et al., "Sensing and control in dual-recycling laser interferometer gravitational-wave detectors," Appl. Opt. **42**, 1244-1256 (2003)

Electro-Magnetic (EM) Fields

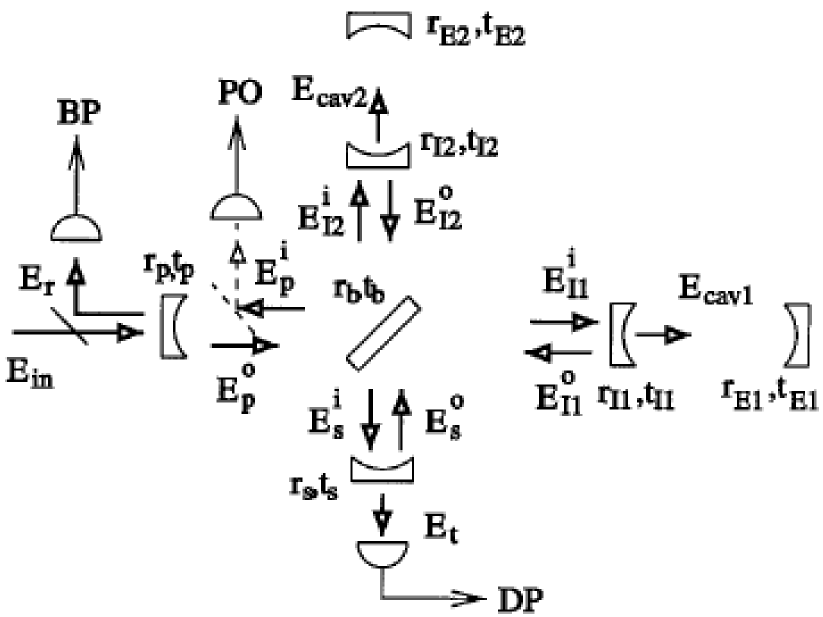


Fig. 5. Fields at the different locations in the interferometer. E_r is the field that is reflected at the power-recycling mirror outside of the interferometer. It will be detected at the bright port (BP). E_t is the field that is transmitted through the whole interferometer. It will be detected at the dark port (DP). The subscript n of all the other fields $E_n{}^m$ denotes the mirror at which the field is calculated. The superscript m denotes the direction of the field. The pickoff (PO) field is proportional to $E_p{}^o$.

$$
\begin{aligned}
E_r &= t_p E_p{}^i + r_p E_{\text{in}}, \\
E_t &= t_s E_s{}^i, \\
E_p{}^o &= -r_p E_p{}^i + t_p E_{\text{in}}, \\
E_p{}^i &= r_b E_{I2}{}^o \exp[-ik(l_p + l_2)] + t_b E_{I1}{}^o \\
&\quad \times \exp[-ik(l_p + l_1)], \\
E_s{}^o &= r_s E_s{}^i, \\
E_s{}^i &= -r_b E_{I1}{}^o \exp[-ik(l_s + l_1)] + t_b E_{I2}{}^o \\
&\quad \times \exp[-ik(l_s + l_2)], \\
E_{I1}{}^i &= -r_b E_s{}^o \exp[-ik(l_s + l_1)] + t_b E_p{}^o \\
&\quad \times \exp[-ik(l_p + l_1)], \\
E_{I1}{}^o &= r_{\text{cav1}}(k) E_{I1}{}^i, \\
E_{I2}{}^i &= r_b E_p{}^o \exp[-ik(l_p + l_2)] + t_b E_s{}^o \\
&\quad \times \exp[-ik(l_s + l_2)], \\
E_{I2}{}^o &= r_{\text{cav2}}(k) E_{I2}{}^i.
\end{aligned}
$$

From K. A. Strain et al., "Sensing and control in dual-recycling laser interferometer gravitational-wave detectors," Appl. Opt. **42**, 1244-1256 (2003)

EM fields including sidebands

$$E_{\rm in} = E_0 \exp[i(\omega_0 t + m \sin \Omega t)]$$

$$\approx E_0 \left\{ \exp(i\omega_0 t) + \frac{m}{2} \exp[i(\omega_0 + \Omega)t] - \frac{m}{2} \exp[i(\omega_0 - \Omega)t] \right\}, \quad (1)$$

IFO Transfer Function for the carrier

Sideband amplitude (previously J_1)

$$E_{\rm out} = E_0 \left\{ T_0 \exp(i\omega_0 t) + \frac{m}{2} T_+ \exp[i(\omega_0 + \Omega)t] - \frac{m}{2} T_- \exp[i(\omega_0 - \Omega)t] \right\}, \quad (2)$$

From K. A. Strain et al., “Sensing and control in dual-recycling laser interferometer gravitational-wave detectors,” Appl. Opt. **42**, 1244-1256 (2003)

Photocurrents

$$I \propto |E_0|^2 + 2m|E_0|^2\{\mathfrak{R}[T_0(T_+^* - T_-^*)]\cos(\Omega t) + \mathfrak{I}[T_0(T_+^* + T_-^*)]\sin(\Omega t)\}, \qquad (4)$$

Quadrature

PDH error signal

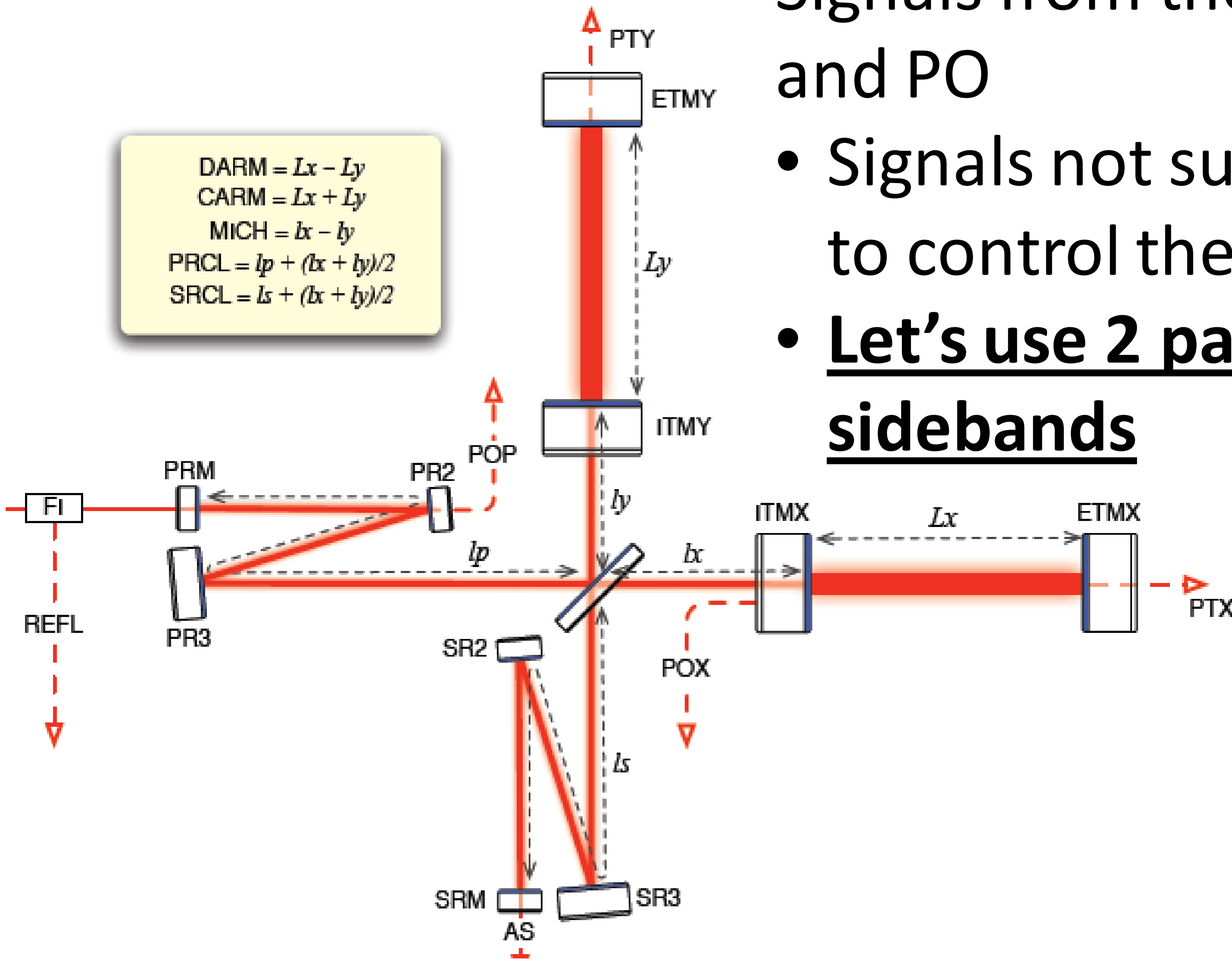
$$S = 2\mathfrak{R}[T_0(T_+^* - T_-^*)]\cos(\alpha) - 2\mathfrak{I}[T_0(T_+^* + T_-^*)]\sin(\alpha), \qquad (5)$$

In-phase

From K. A. Strain et al., "Sensing and control in dual-recycling laser interferometer gravitational-wave detectors," Appl. Opt. **42**, 1244-1256 (2003)

Signals from the BP, DP and PO

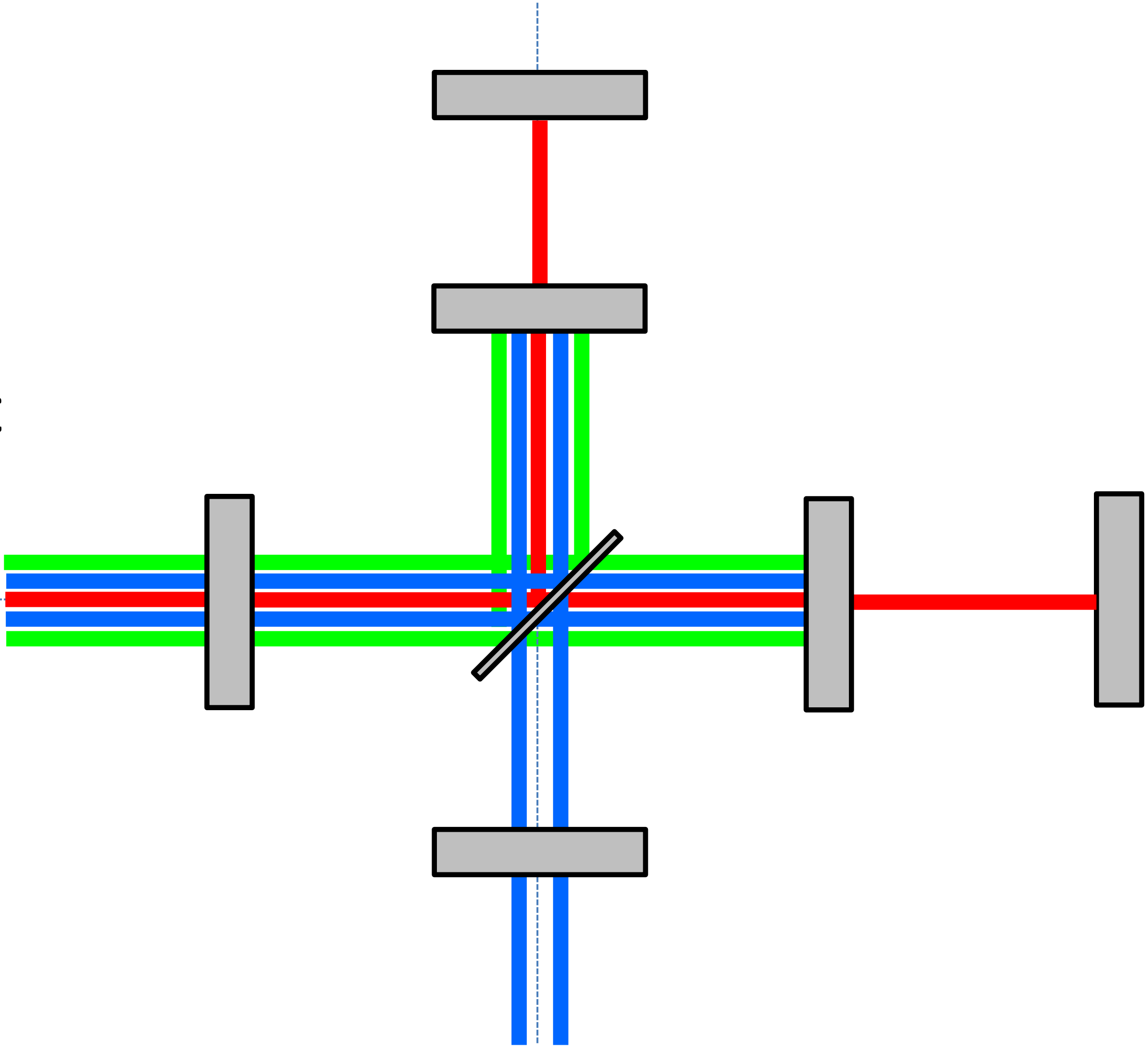
- Signals not sufficient to control the 5 DOF
- **<u>Let’s use 2 pairs of sidebands</u>**



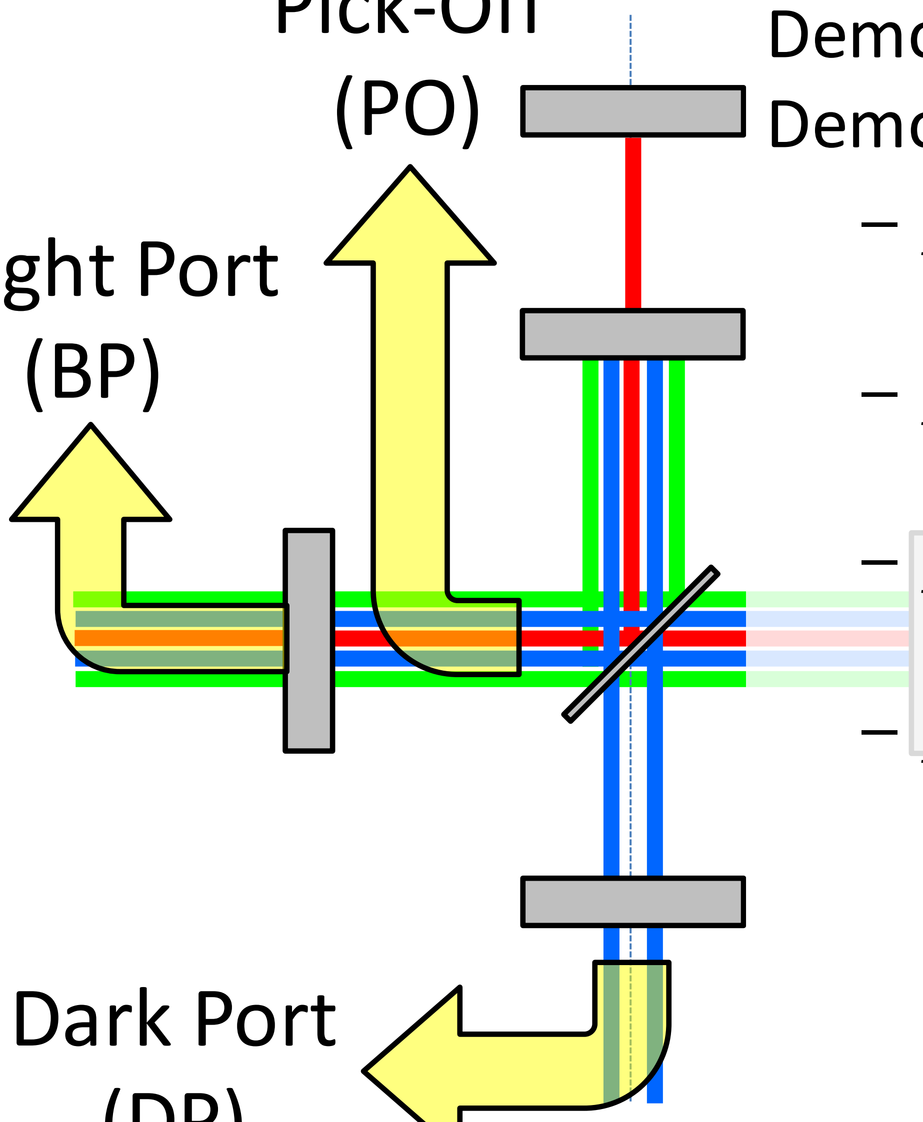
From “The Advanced LIGO LSC Final Design Document” T1000298

Two Modulation Frequencies (High and Low)

- Carrier
- Sideband
  - High frequency (f_2 = 45 MHz)
  - Chosen so as to couple to both PRC and SRC
- Sideband
  - Low frequency (f_1 = 9 MHz)
  - Chosen so as to couple just to the PRC



Error Signals



Demodulation and Double-Demodulation at

- $f_1 (9\ MHz)$
  - beat of carrier to sideband 1
- $f_2 (45\ MHz)$
  - beat of carrier to sideband 2
- $f_1 + f_2\ (54\ MHz)$
  - beat of sideband 1 to sideband 2
- $f_2 - f_1\ (36\ MHz)$
  - beat of sideband 1 to sideband 2

AdvLIGO Sensing Matrix

From "AdvLIGO Interferometer Sensing and Control Conceptual Design" T070247 and LSC Final Design T1000298

3.1 Sensing matrix

The following sensing matrices for Scien[illegible] in Optickle:

Demodulated at $f_1 = 9\ MHz$

Demodulated at $f_2 = 45\ MHz$

Demodulated at $f_2 - f_1 = 36\ MHz$

Sensing Matrix in Watts per mete[illegible] (NS/NS inspiral)

Port	CARM	DARM	PRCL	MICH	SRCL
REFL I1	9.4e+08	2e+05	7.3e+07	1.1e+06	5.5e+03
AS DC	1.3e+06	4.2e+09	2.8e+05	1.5e+07	7.6e+06
POP I1	3.2e+07	6.7e+03	1.[illegible]	[illegible]	3.1e+02
POP Q2	1.5e+07	2.3e+04	1.[illegible]	[illegible]	3e+04
REFL IM	1.4e+06	2.5e+04	5.[illegible]	[illegible]	2.8e+05

Sensing Matrix in Watts per me[illegible]e 1 (zero detuning)

Port	CARM	DARM	PRCL	MICH	SRCL
REFL I1	9.4e+08	1.3e+0[illegible]	[illegible]	[illegible]	1.4e+04
AS DC	3e+06	9.7e+0[illegible]	[illegible]	[illegible]	7e+03
POP I1	3.2e+07	4.4e+0[illegible]	[illegible]	[illegible]	3e+02
POP Q2	8.7e+06	4.2e+0[illegible]	[illegible]	[illegible]	8.8e+04
POP I2	8.7e+06	9e+03	1.8e+06	9.9e+04	3e+05

The contractions used in the port name are: I: I-phase, Q: Q-phase, 1: demodulated at f_1, 2: demodulated at f_2, M: demodulated at $f_2 - f_1$, P: demodulated at $f_2 + f_1$. The main matrix elements are in bold red. The biggest worrisome elements are in blue. The full sensing matrix with all available ports is shown in Figures 20 and 21 of appendix A.

Non-diagonal Sensing Matrix

From "AdvLIGO Interferometer Sensing and Control Conceptual Design" T070247 and LSC Final Design T1000298

Main elements

3.1 Sensing matrix

The following sensing matrices for Science mode 1 and 2 were calculated in Optickle:

Sensing Matrix in Watts per meter at 1 kHz, for Science Mode 2 (NS/NS inspiral)

Port	CARM	DARM	PRCL	MICH	SRCL
REFL I1	9.4e+08	2e+05	7.3e+07	1.1e+06	5.5e+03
AS DC	1.3e+06	4.2e+09	2.8e+05	1.5e+07	7.6e+06
POP I1	3.2e+07	6.7e+03	1.2e+07	6.8e+03	3.1e+02
POP Q2	1.5e+07	2.3e+04	1.4e+06	4.3e+05	3e+04
REFL IM	1.4e+06	2.5e+04	5.1e+06	4.5e+05	2.8e+05

Sensing Matrix in Watts per meter at 1 kHz, for Science Mode 1 (zero detuning)

Port	CARM	DARM	PRCL	MICH	SRCL
REFL I1	9.4e+08	1.3e+05	7.3e+07	1e+06	1.4e+04
AS DC	3e+06	9.7e+09	6.7e+05	3.4e+07	7e+03
POP I1	3.2e+07	4.4e+03	1.2e+07	6.6e+03	3e+02
POP Q2	8.7e+06	4.2e+04	4.6e+05	7.4e+05	8.8e+04
POP I2	8.7e+06	9e+03	1.8e+06	9.9e+04	3e+05

The contractions used in the port name are: I: I-phase, Q: Q-phase, 1: demodulated at f_1, 2: demodulated at f_2, M: demodulated at $f_2 - f_1$, P: demodulated at $f_2 + f_1$. The main matrix elements are in bold red. The biggest worrisome eleme matrix with all available ports is shown in Figures 20 an

Elements off-diagonal

DC readout: A bit of history

- Radio Frequency (RF) modulation
  - Heterodyne detection scheme
  - Modulation-demodulation gives rise to the PDH error signal
- Initial LIGO
  - Four DOFs, sensed and controlled by this heterodyne scheme
  - Differential arm motion L_- measured by the Dark Port quadrature error signal (AS_Q)
  - Large signal swings found in the Dark Port inphase signal (AS_I)
    - Due to "junk" light
    - Would saturate the RF electronics

From Rana Adhikari “DC Readout” G050091

Problem with *heterodyning* at the DP

Photodetectors

- Large AS_I signal limits the power on each PD to ~20 mW (leaving some headroom)
- Scaling to the full LIGO-I power of 8W or 50 W in an upgrade would lead to a giant forest of PDs and an associated forest of AS_I servos, mixers, ADCs, CPUs, etc.... **Big headache!**

# of AS port diodes

	RF	DC
L1	4	1
H1	8	1
H2	24	1

- ✓ DC: No RF electronics!
- ✓ Easy photodetector design. Don't care about diode capacitance: can select based on QE, spatial uniformity (EG&G 5 mm PD?)
- ✓ With the OMC, the $C_D \sim 5 \times 10^{-6}$
- ✓ 50 W into the MC
  - -> 1800 W on the BS
  - -> C_D = 10 mW!
- ✓ Including the arm offset $P_{AS} \sim 20$ mW

This i

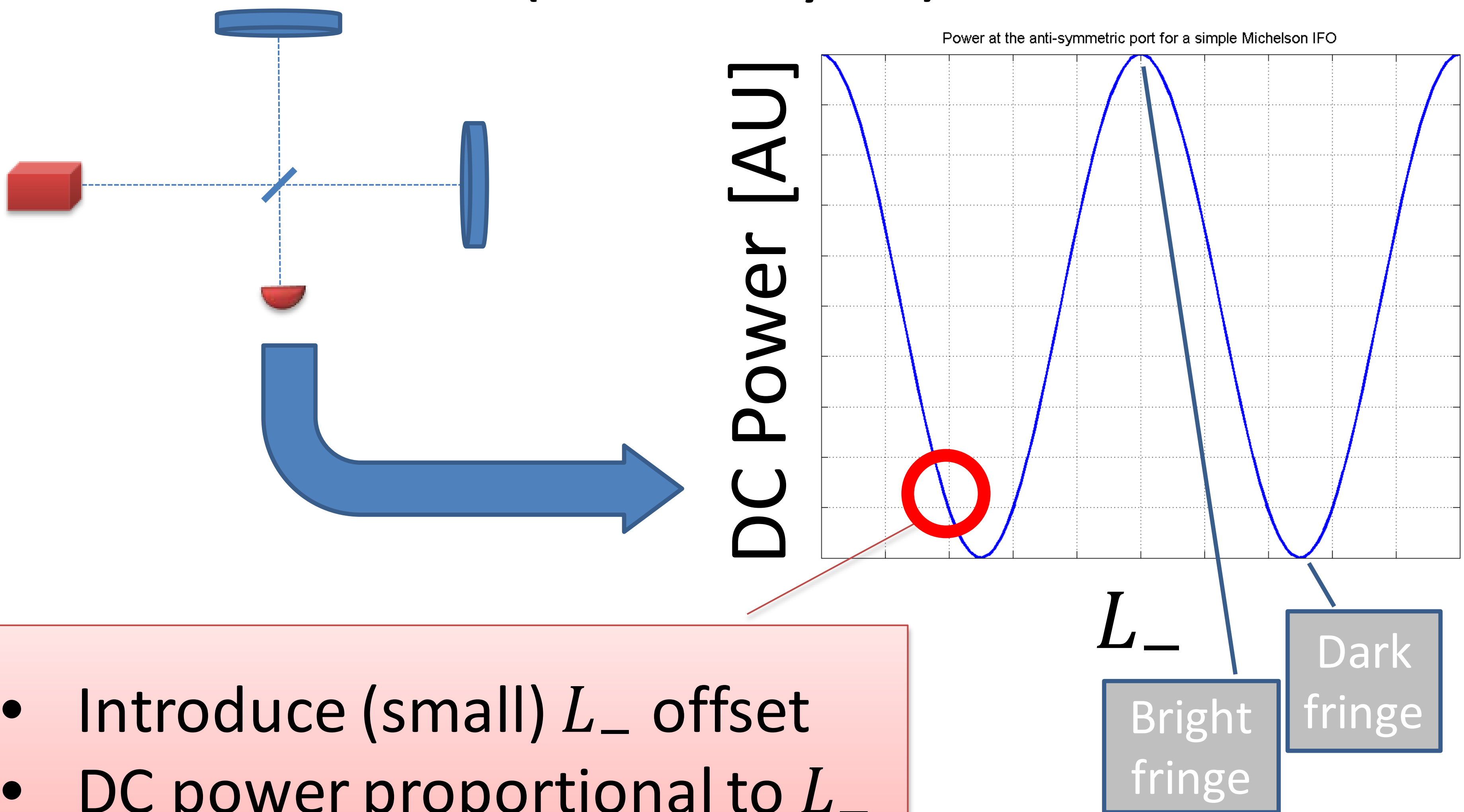
Being
40m l

DC Readout in 2006

G050091-00-D

Proposed solution: *homodyne* detection scheme

Overview of DC Readout (Homodyne)



- Introduce (small) L_- offset
- DC power proportional to L_-
- Advanced LIGO's GW channel

Expected AdvLIGO sensitivity to GWs

From "AdvLIGO Interferometer Sensing and Control Conceptual Design" T070247

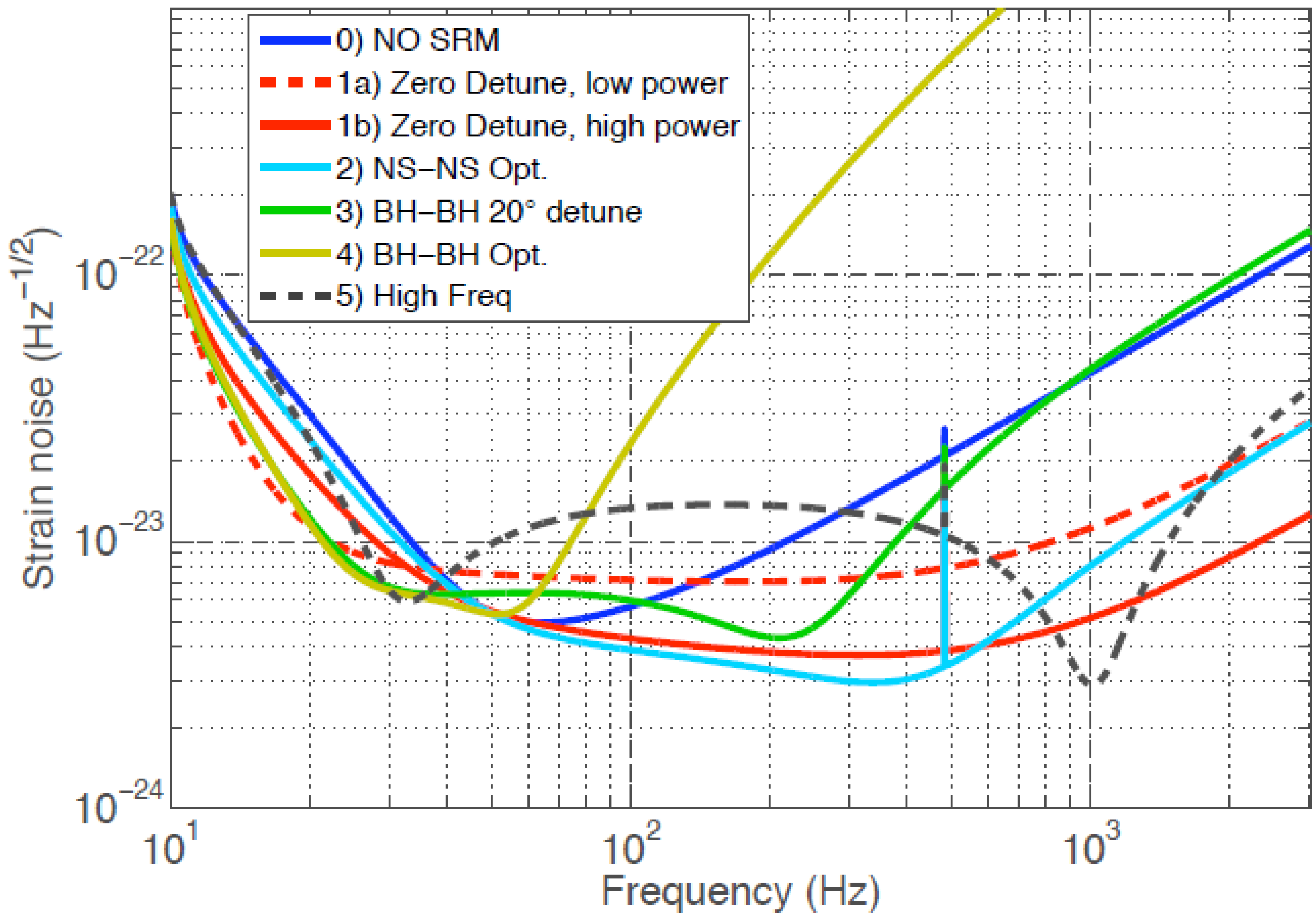


Figure 1: Proposed modes of operation for the Advanced LIGO interferometers. See tex for description of the modes.

So far…

- Advanced LIGO optical configuration
  - Dual-recycling laser interferometer
  - Signal Recycling Cavity
    - Introduces a tunable frequency response
- Longitudinal Degrees of Freedom to Sense and Control
  - From four (initial LIGO) to five
  - Added level of complexity → need two pairs of sidebands
  - Demodulation and Double-Demodulation ($f_1, f_2, f_1 + f_2, f_2 - f_1$)
- Non-diagonal sensing matrix
- Homodyne detection scheme
  - Get around heterodyne detection scheme at the DP
  - Requires to lock at small L_- offset

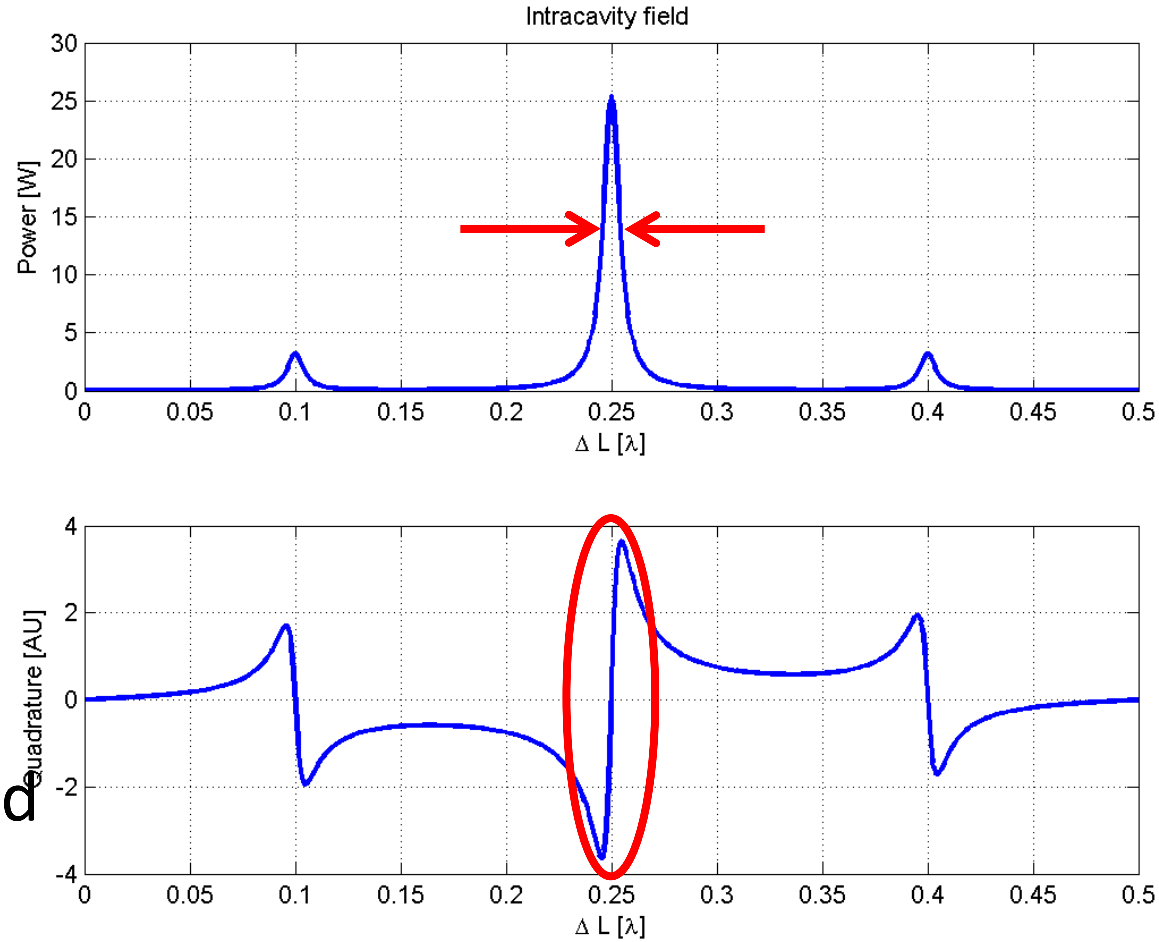
AdvLIGO Length Sensing and Control (LSC) Requirements

1. Bring the Advanced LIGO IFO to the desired operating point
2. Hold the IFO at the operating point
3. Provide GW signal

From "The AdvLIGO Length Sensing and Control Final Design" T1000298

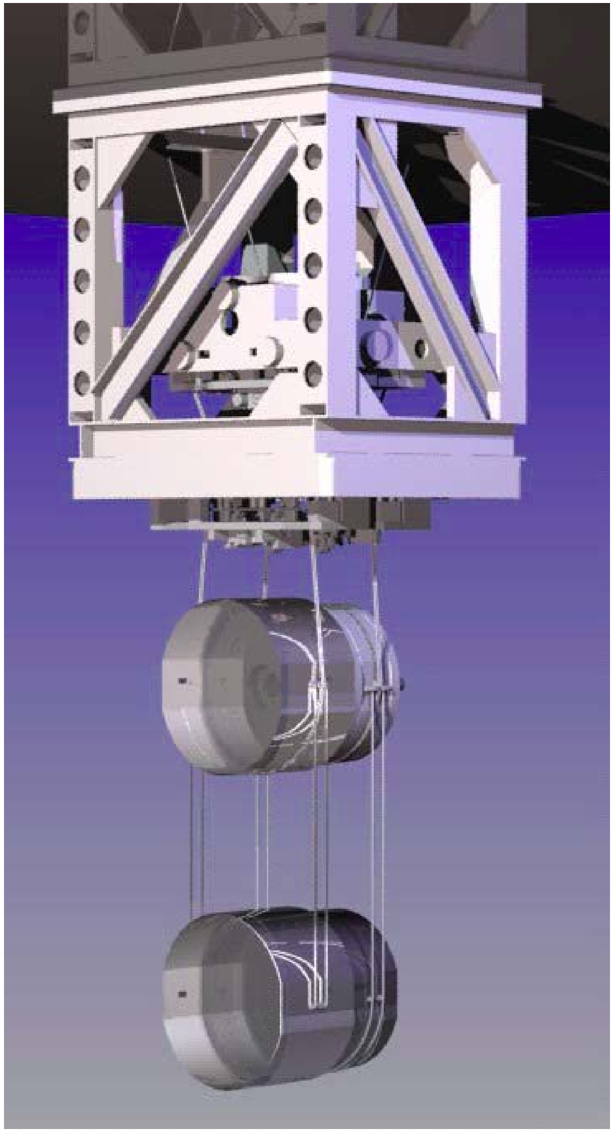
Guiding IFO to the operating point: Problem of Lock Acquisition

- Narrow linewidth ($\sim 1\ nm$)
  - Residual arm motion of $\sim 1\ \mu m$ RMS at $\sim 1\ Hz$
- Coupling of multiple optical cavities
- Cannot simply turn control system on and wait



Problem of Lock Acquisition

- In addition, Test Mass (TM) actuators will lack sufficient authority when cavities are freely swinging
  - For AdvLIGO (compared with Initial LIGO):
    - weaker TM actuators
    - heavier TMs
- Guiding IFO to operating point is an issue
  - Standard PDH locking scheme not reliable
  - Lock acquisition cannot be a systematic process (cooling and heating of TMs an issue)
  - Impact on detector's duty cycle



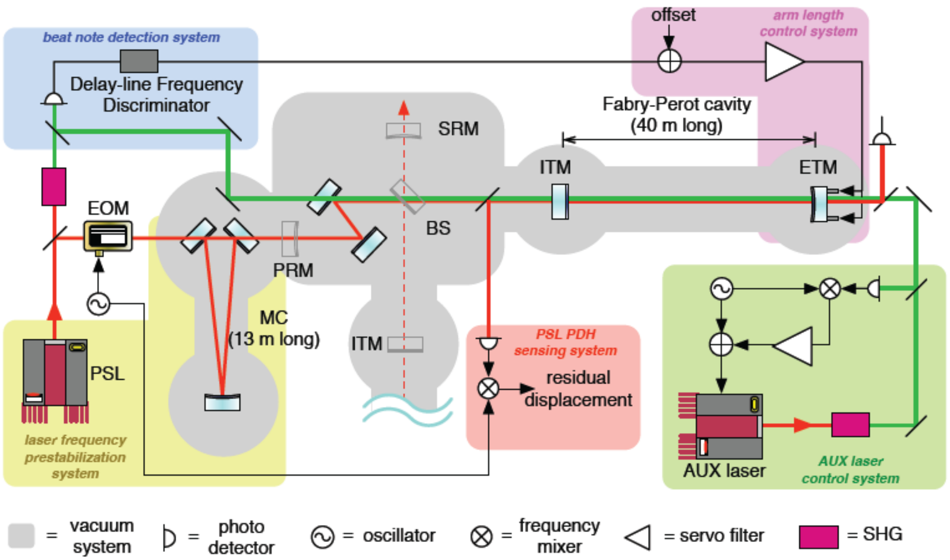
Strategy

1. Maintain both arm cavities at a fixed (large) offset from resonance
   - Reduce RMS cavity motion to less than cavity linewidth ($\sim 1\,nm$)
2. Lock the central degrees of freedom first
   - (l_s, l_+ and l_-)
3. Remove cavity offset and bring arms into resonance (IFO @ operating point)
4. Switch control to standard heterodyne/homodyne operation

How?

Green Laser Locking

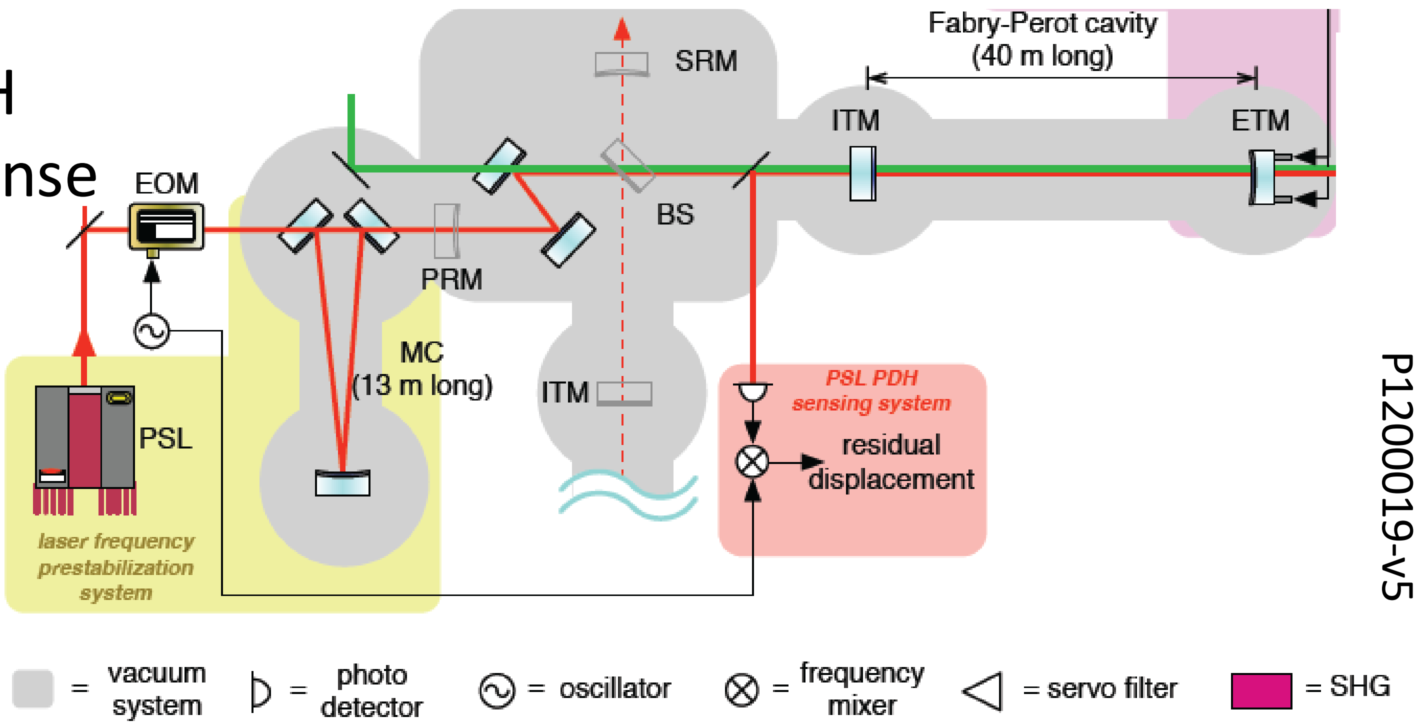
- To significantly increase detector's duty cycle
  - Auxiliary sensing and control system for the arm cavities
- Dual-wavelength locking designed to
  a. maintain both arm cavities at a fixed offset from resonance
  b. reduce RMS motion to within cavity linewidth
- Experimentally tested at Caltech's 40 m



(see Rollins J. et al., "Multi-color Cavity Metrology" P1200019-v5 and Mullavey A. J. et al, "Arm-length stabilization for interferometric gravitational-wave detectors using frequency-doubled auxiliary lasers," Optics Express, **20**, 81-89 (2011))

Multi-color Cavity Metrology at the 40 m

- Green laser locking
- Apply process to single arm at Caltech's 40m
- First, use standard PDH scheme to sense TM motion (without control) of single arm

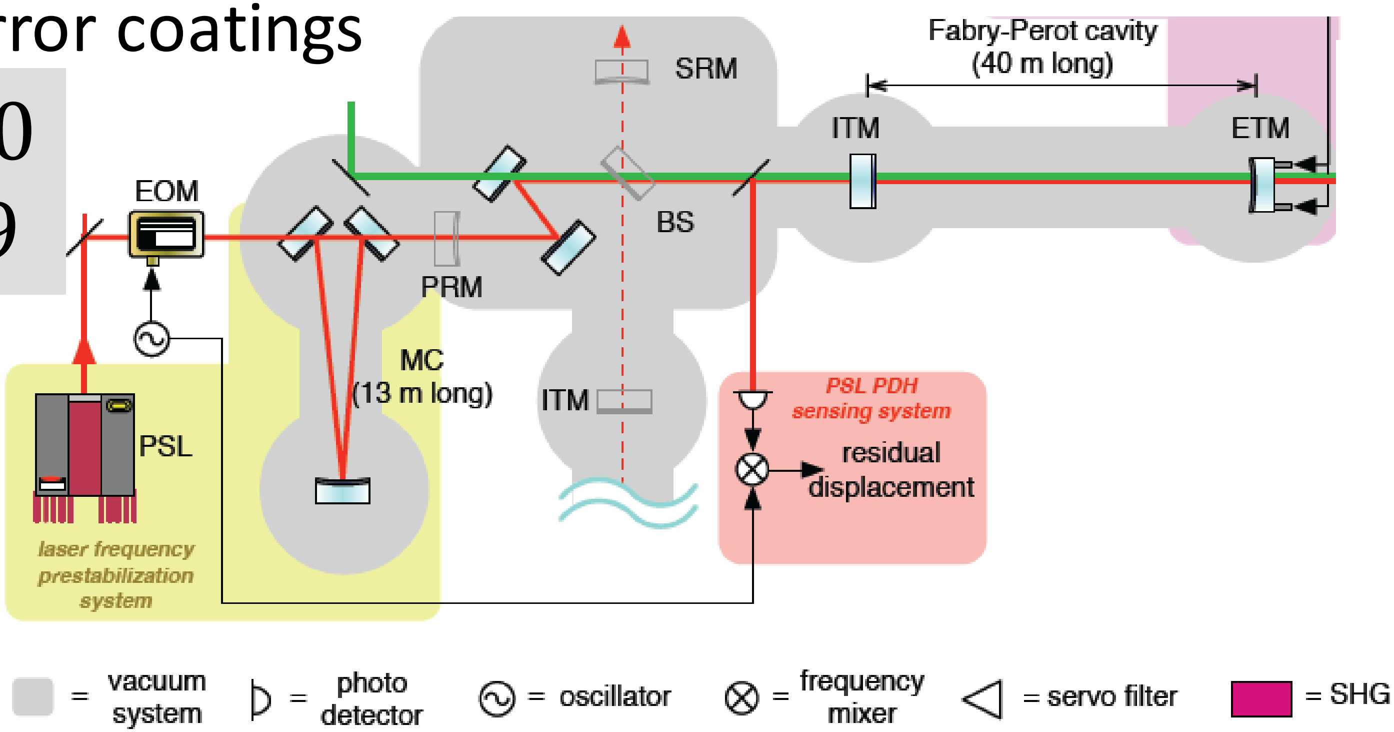


The Auxiliary (AUX) Laser System

- Introduce a frequency-doubled NPRO (532 nm, green)
  - Via second harmonic generation (SHG) in a PPKTP crystal
  - Injected in ETM
- Also modulated producing a 2nd PDH error signal
- Dichroic mirror coatings

$$\mathcal{F}_{1064} = 450$$
$$\mathcal{F}_{532} = 109$$

P1200019-v5

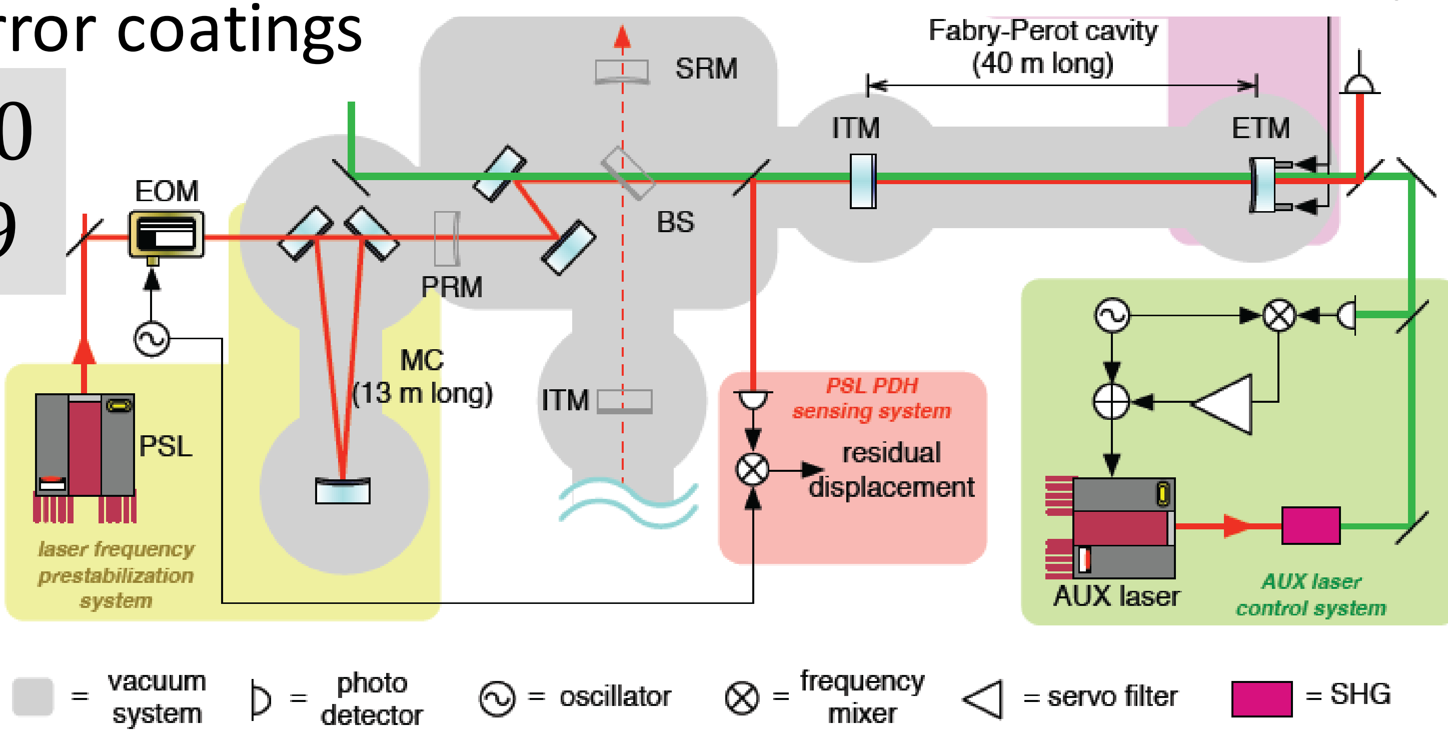


The Auxiliary (AUX) Laser System

- Introduce a frequency-doubled NPRO ($532\ nm$, green)
  - Via second harmonic generation (SHG) in a PPKTP crystal
  - Injected in ETM
- Also modulated producing a 2nd PDH error signal
- Dichroic mirror coatings

$$\mathcal{F}_{1064} = 450$$
$$\mathcal{F}_{532} = 109$$

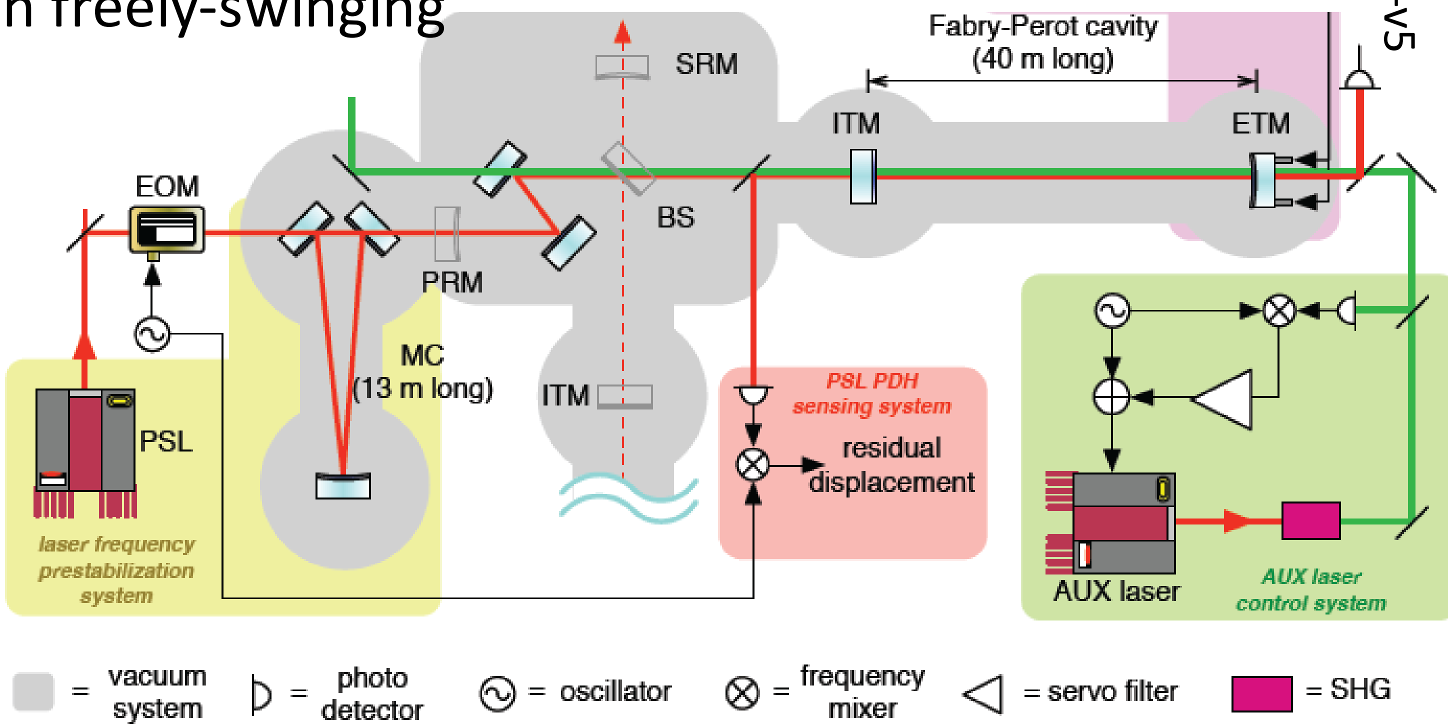
P1200019-v5



Locking of the AUX laser

- At this point, AUX laser frequency locked **to** free-swinging arm cavity
- High-gain and high-bandwidth control
- AUX laser frequency **tracks** cavity length at all times
  - TMs remain freely-swinging

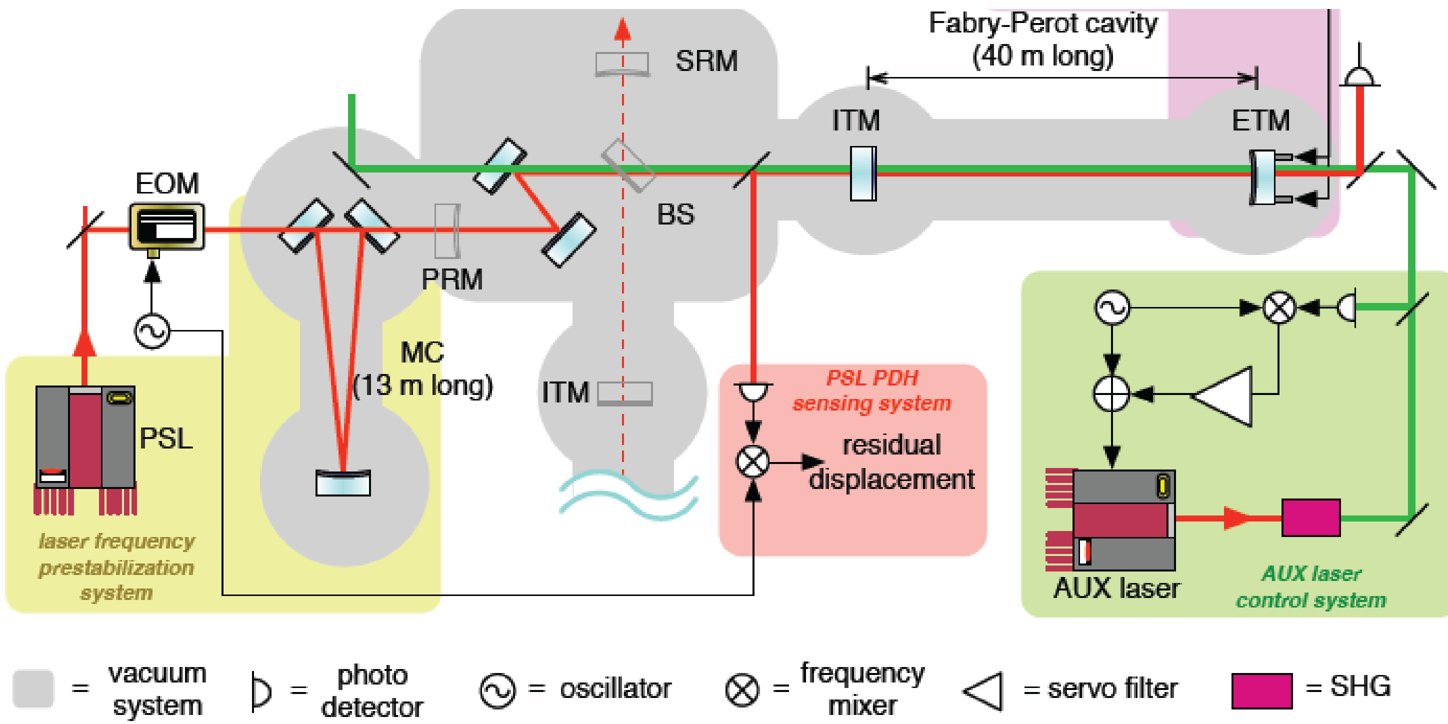
P1200019-v5



Comparing Frequencies

- 532 beam sample compared to 1064 sample
  - 532 laser frequency tracks the cavity length, 1064 is free-running
- Frequency comparison → how far PSL is from resonance
  - Comparison results in a beat note frequency, measured with DFD

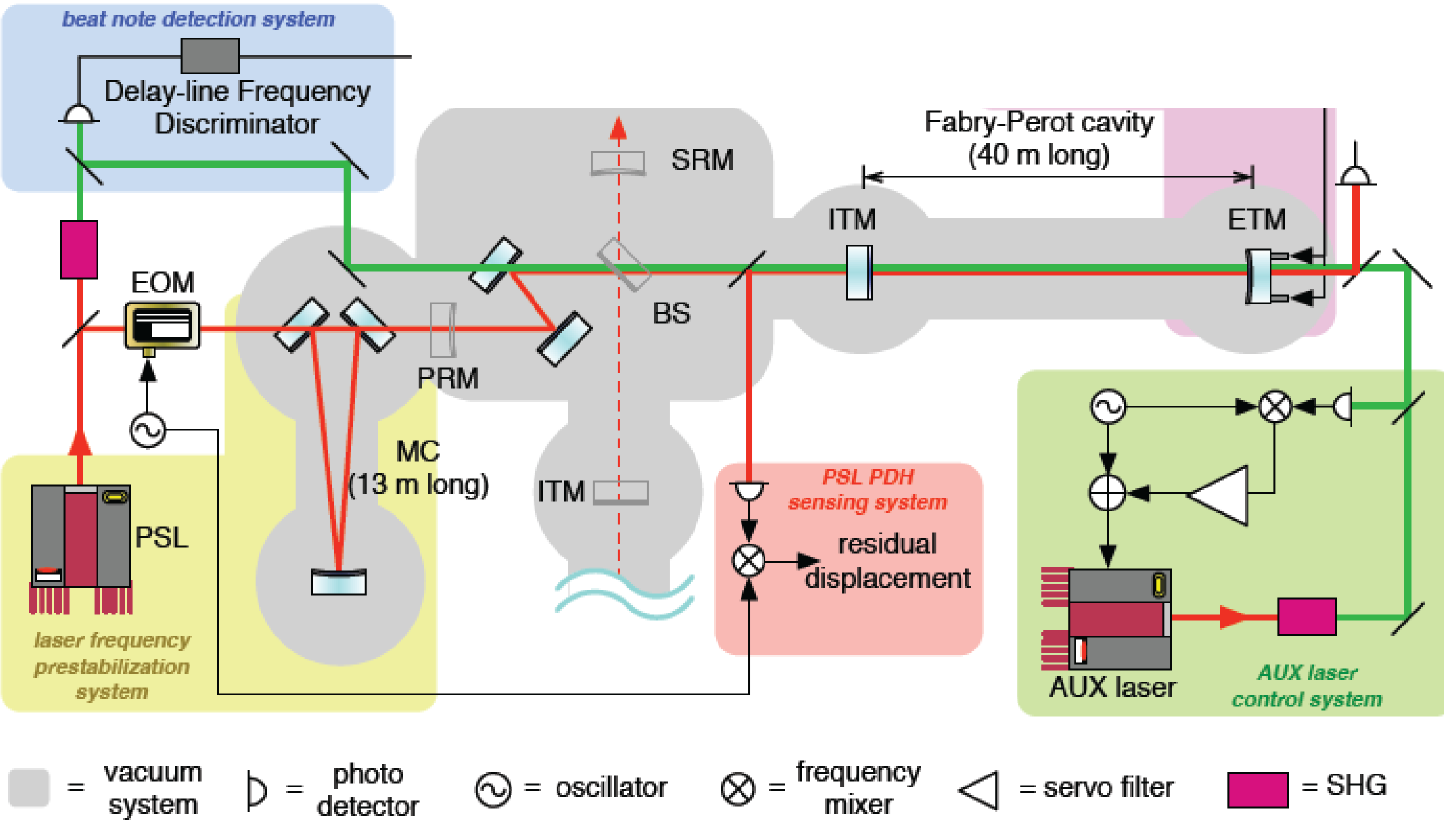
P1200019-v5



Comparing Frequencies

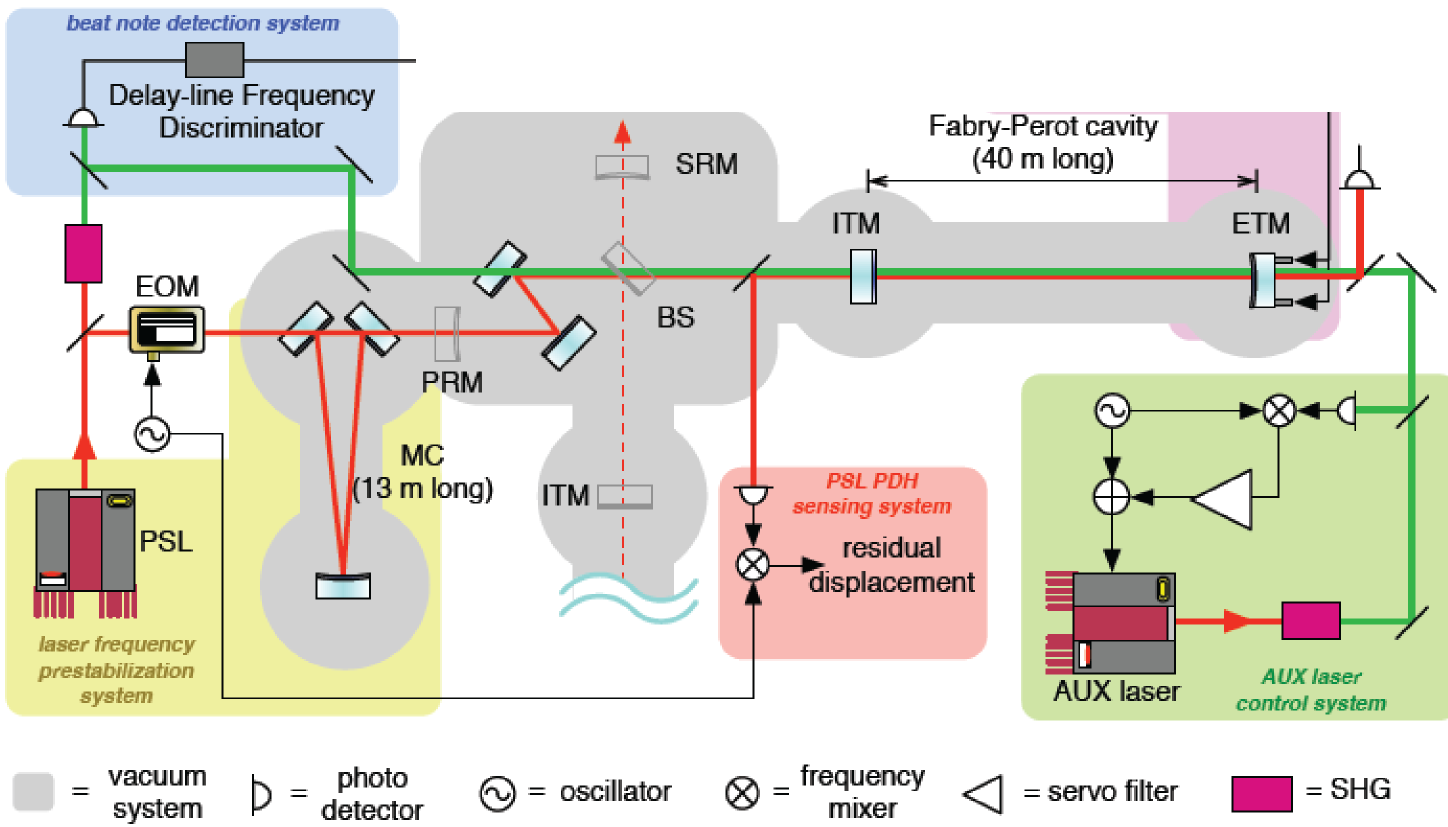
P1200019-v5

- 532 beam sample compared to 1064 sample
  - 532 laser frequency tracks the cavity length, 1064 is free-running
- Frequency comparison → how far PSL is from resonance
  - Comparison results in a beat note frequency, measured with DFD



Suppressing cavity motion

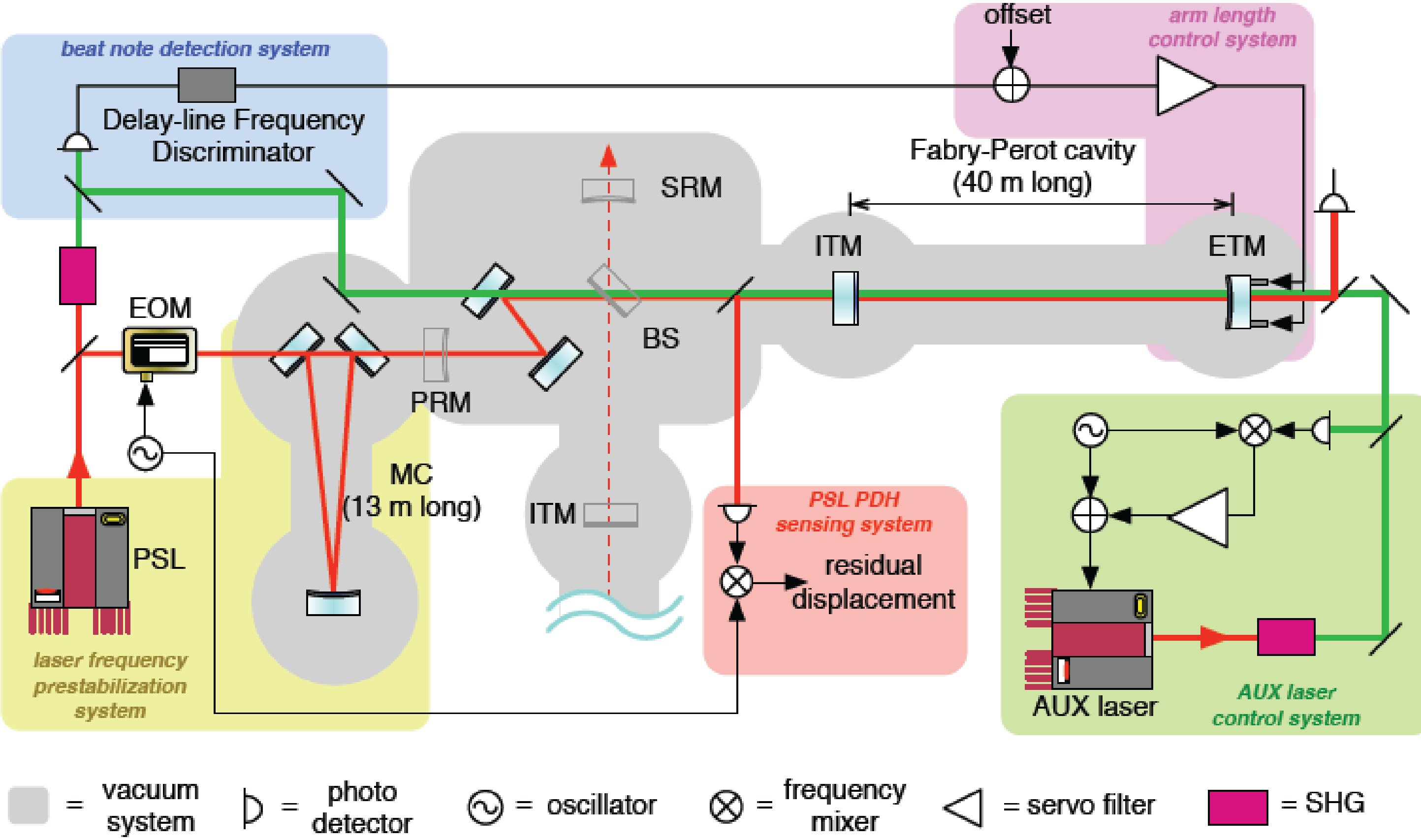
- New error signal
  - Beat frequency used to lock the cavity to the PSL (with the PSL resonating or not)
  - Control signal sent to the ETM, suppressing cavity motion (relative to the PSL)
- Offset allows to change locking point



P1200019-v5

Suppressing cavity motion

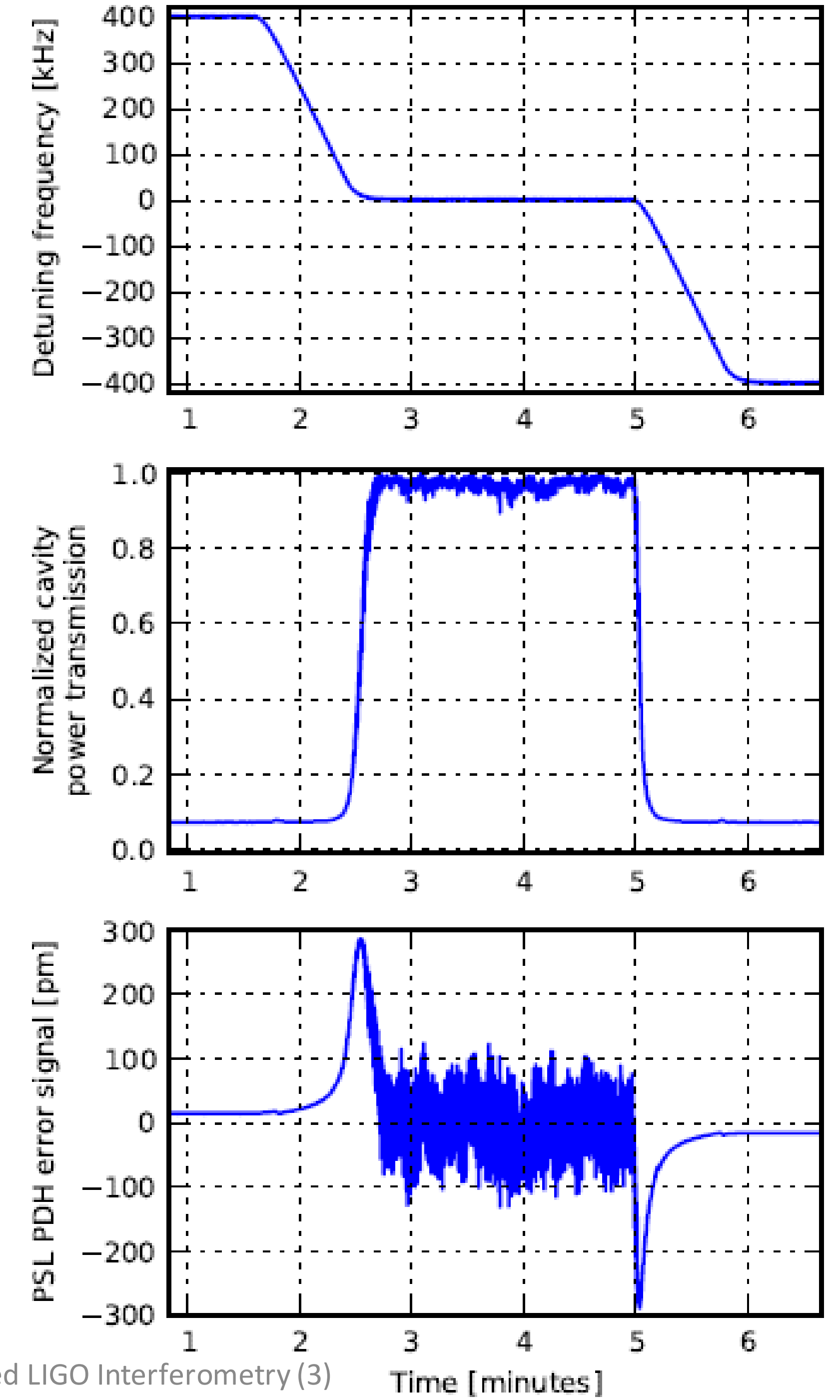
- New error signal
  - Beat frequency used to lock the cavity to the PSL (with the PSL resonating or not)
  - Control signal sent to the ETM, suppressing cavity motion (relative to the PSL)
- Offset allows to change locking point



P1200019-v5

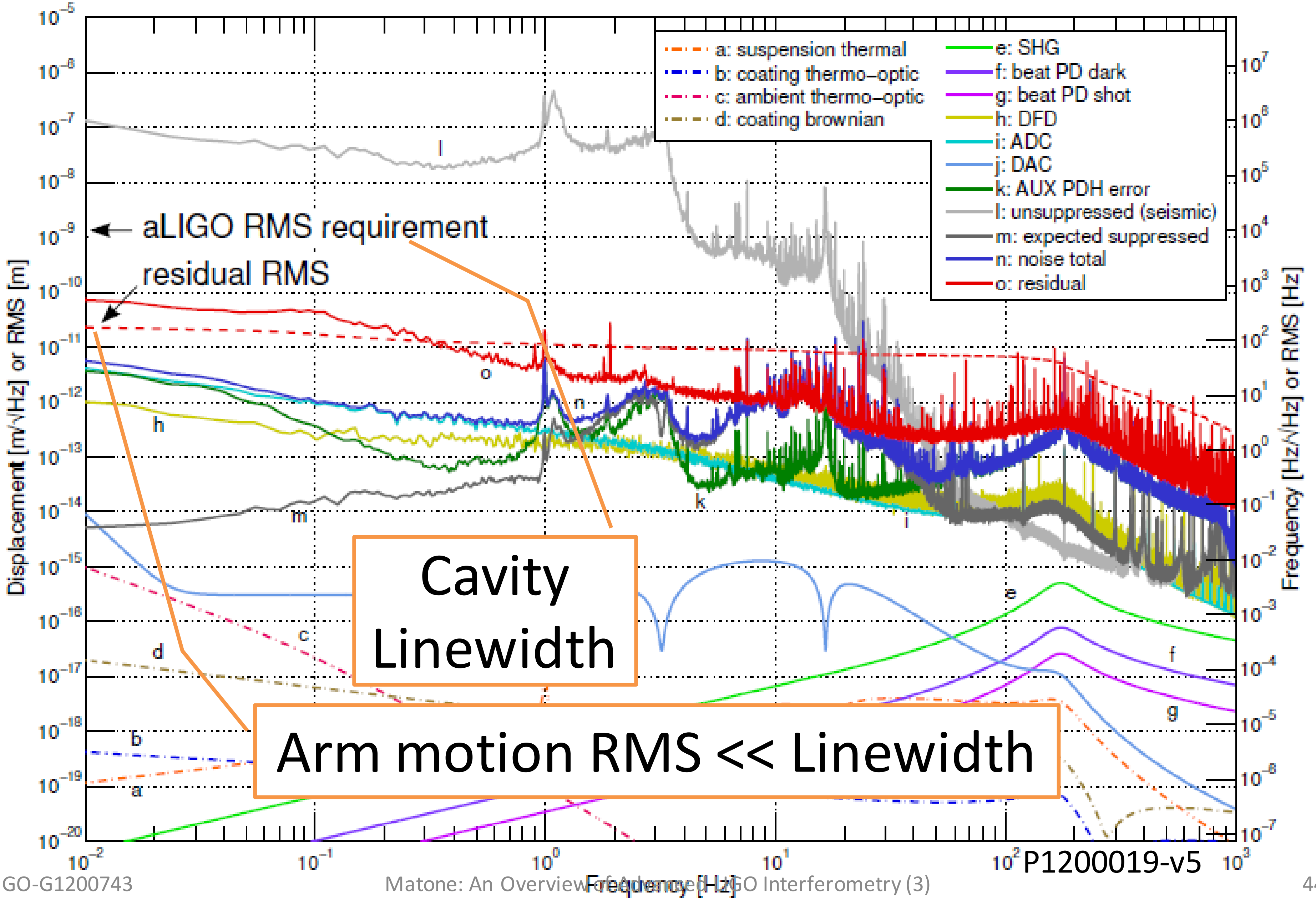
Results

- AUX laser frequency locked to arm
- Arm cavity length locked to PSL (using beat frequency)
- Cavity length offset allows to scan the cavity length, looking for the 1064 resonance
- PSL PDH error signal is used to measure the residual displacement noise



P1200019-v5

Residual Displacement Noise



Adv LIGO Strategy

1. Use AUX laser system to
   a. Lock arms away from resonance
   b. Reduce RMS motion
2. Lock the central degrees of freedom
   – (l_s, l_+ and l_-)
3. Reduce arm offset and bring IFO to operating point

From "AdvLIGO Interferometer Sensing and Control Conceptual Design" T070247-01

Control of l_s, l_+ and l_- during acquisition

- Error signals for the central IFO degrees of freedom
  - Need to be independent of arm cavities
- Signals on reflection and demodulated at 3f have been studied and shown to be independent of arms
  - Modulation frequencies at 27 Hz and 135 Hz

From "AdvLIGO Interferometer Sensing and Control Conceptual Design" T070247-01

So far…

- Advanced LIGO optical configuration
  - Dual-recycling laser interferometer
  - Signal Recycling Cavity
    - Introduces a tunable frequency response
- Longitudinal Degrees of Freedom to Sense and Control
  - Five DOF, added level of complexity, two pairs of sidebands
  - Demodulation and Double-Demodulation ($f_1, f_2, f_1 + f_2, f_2 - f_1$)
- Homodyne detection scheme
  - Get around heterodyne detection scheme at the DP
  - Requires to lock at small L_- offset
- Lock Acquisiton
  - Green laser locking: AUX laser system to stabilize LIGO arms, locking them away from resonance
  - Lock central degrees of freedom (demodulating at $3f$)
  - Bring arms into resonance
  - Switch control to standard heterodyne/homodyne operation

Group Activity

- Post questions on the board
- Group discussion
- In preparation for tomorrow
  - Read “The Advanced LIGO Reference Design” M060056-v2
  - Prepare questions