An Overview of Advanced LIGO Interferometry

Luca Matone
Columbia Experimental Gravity group (GECo)

Jul 16-20, 2012

LIGO-G1200743

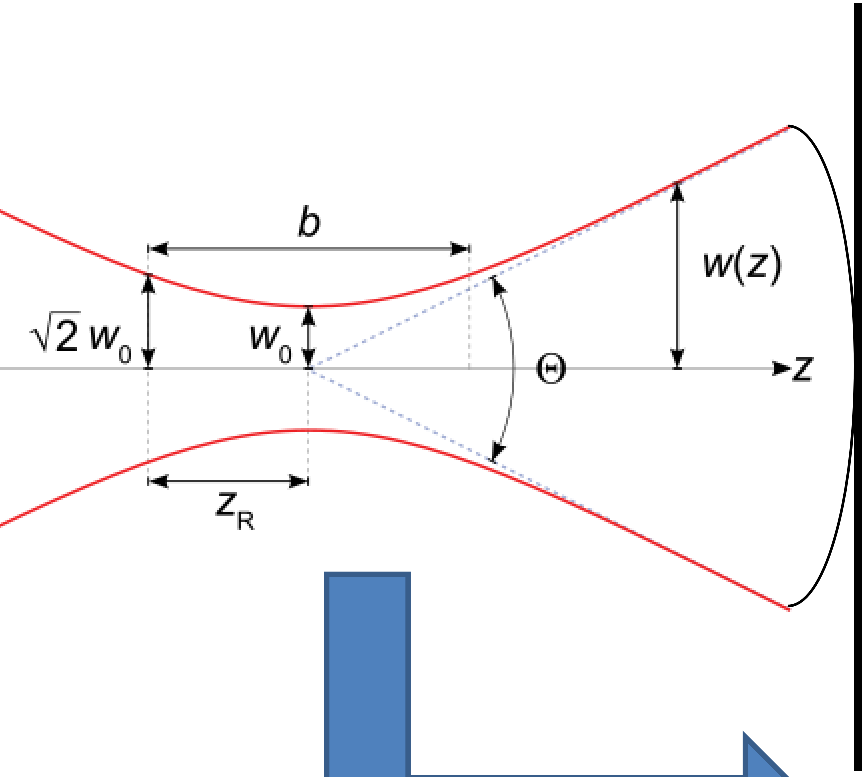
So far…

- 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

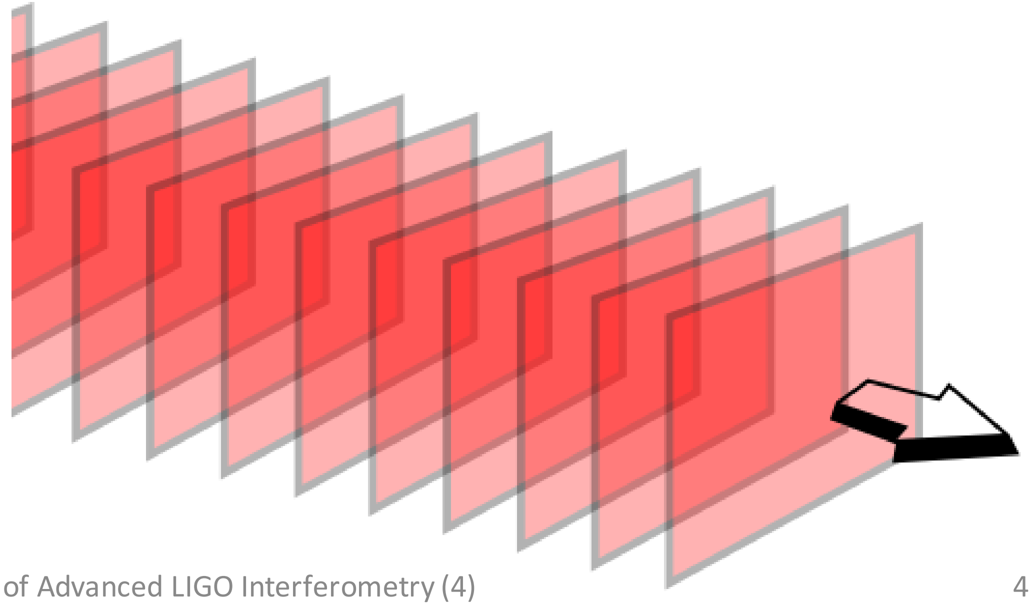
Mode Cleaners and Alignment

- Input laser beam needs to be “matched” to IFO
  - Maximize light power coupling to IFO
- Laser frequency and beam jitter noise needs to be reduced
  - “Common” noise term couples to the Dark Port
- TM angular noise needs to be mitigated
  - Misalignments also couple to the DP
- Limit to IFO sensitivity

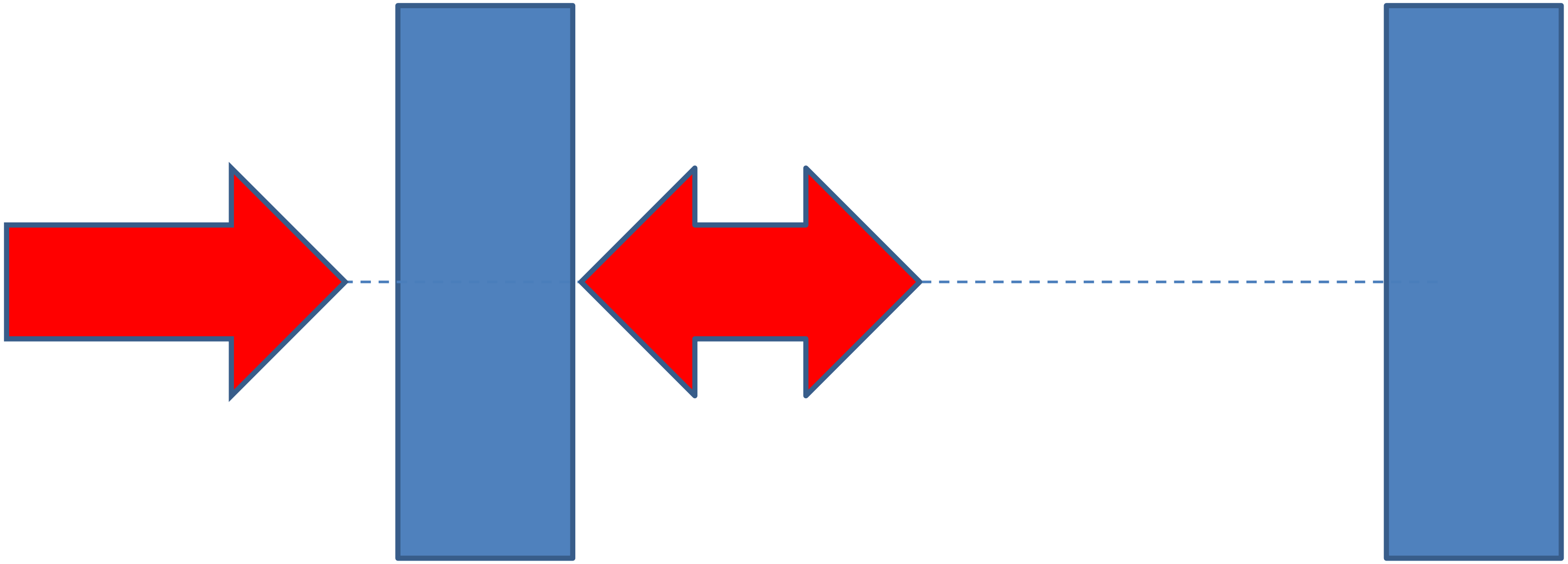
Recall: Plane-Wave Approximation



Flat wavefront
(like that of a plane wave)

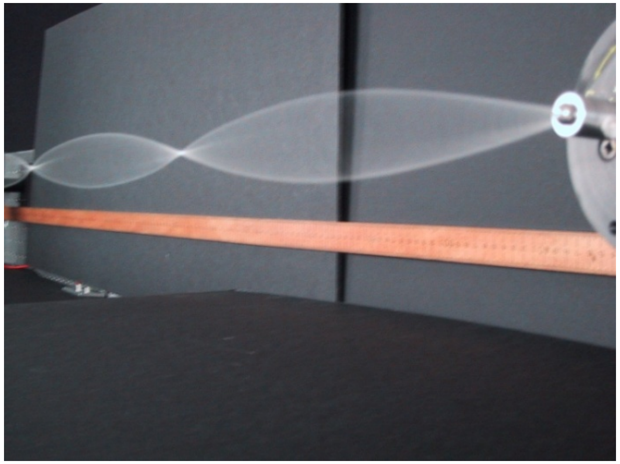


Stable Optical Resonator

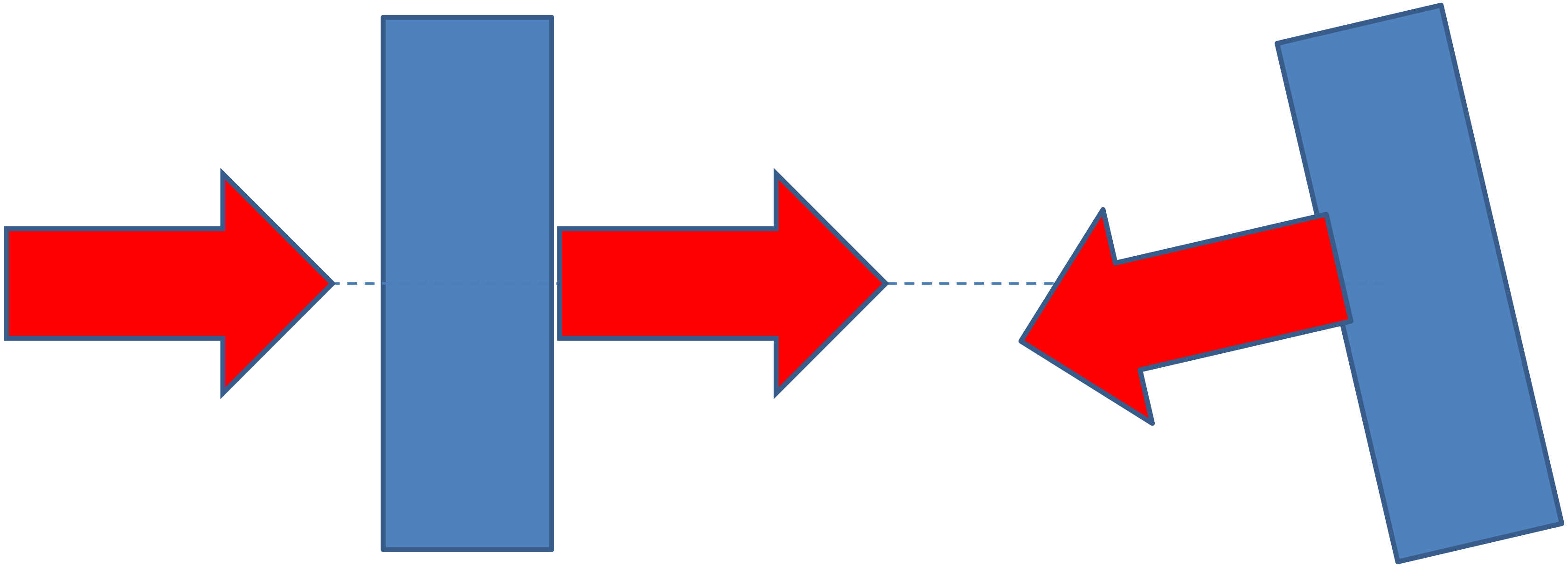


H. Kogelnik and T. Li, *Appl. Opt.* **5**, 1550 (1966)

1. Light rays reflect multiple times.
2. Rays reflect onto themselves
3. Constructive interference forms a standing wave within the cavity

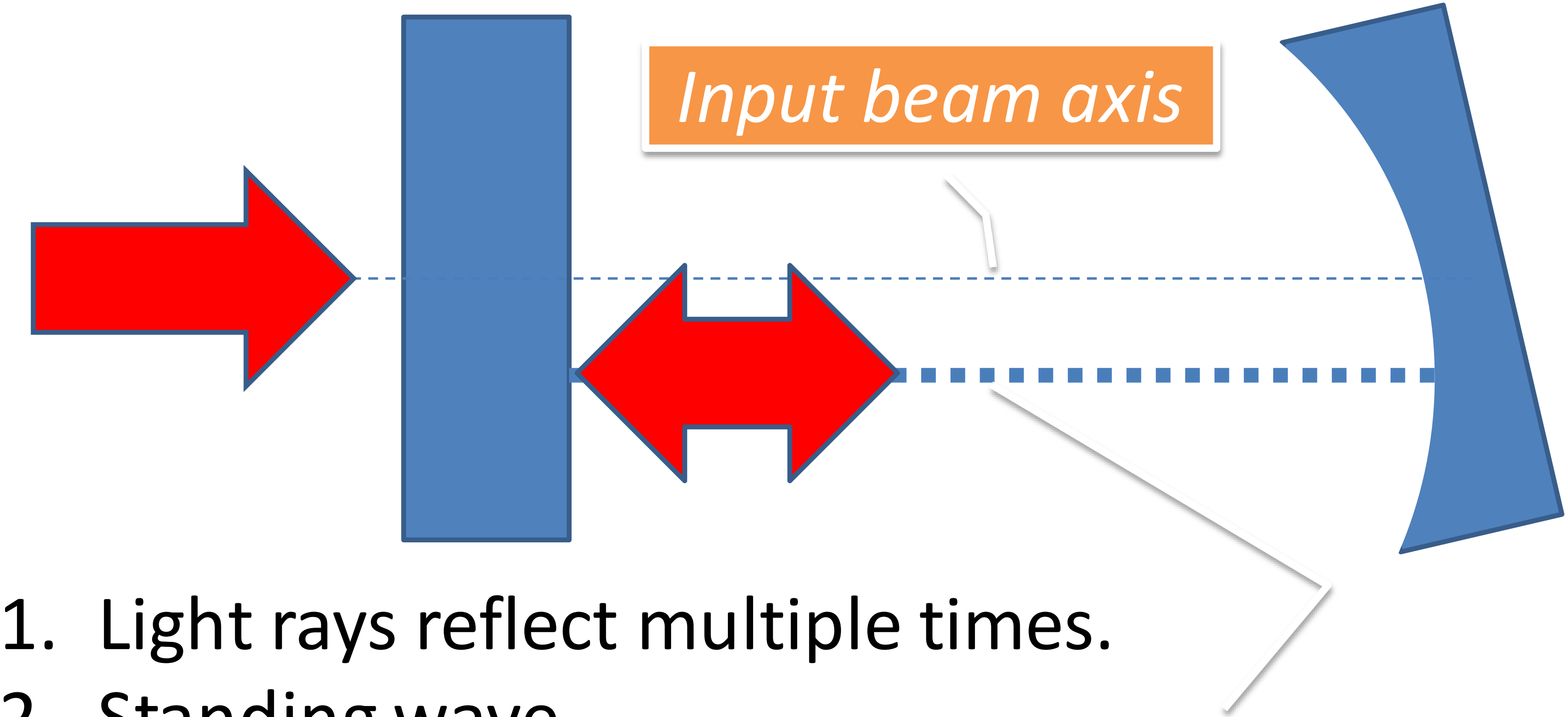


Misalignment



1. Light rays reflect multiple times but ...
2. Rays don’t return onto themselves
3. No standing wave (unstable resonator)

Plane-Concave Cavities

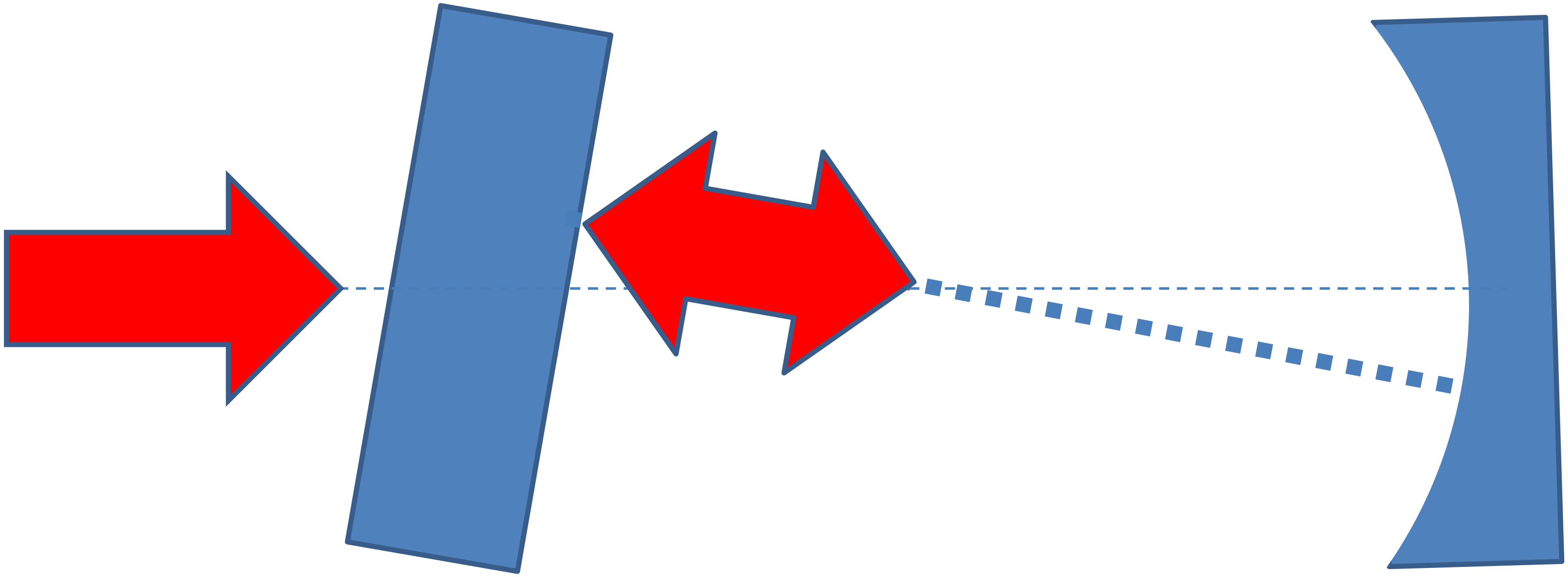


Input beam axis

Cavity axis: offset with respect to input beam axis

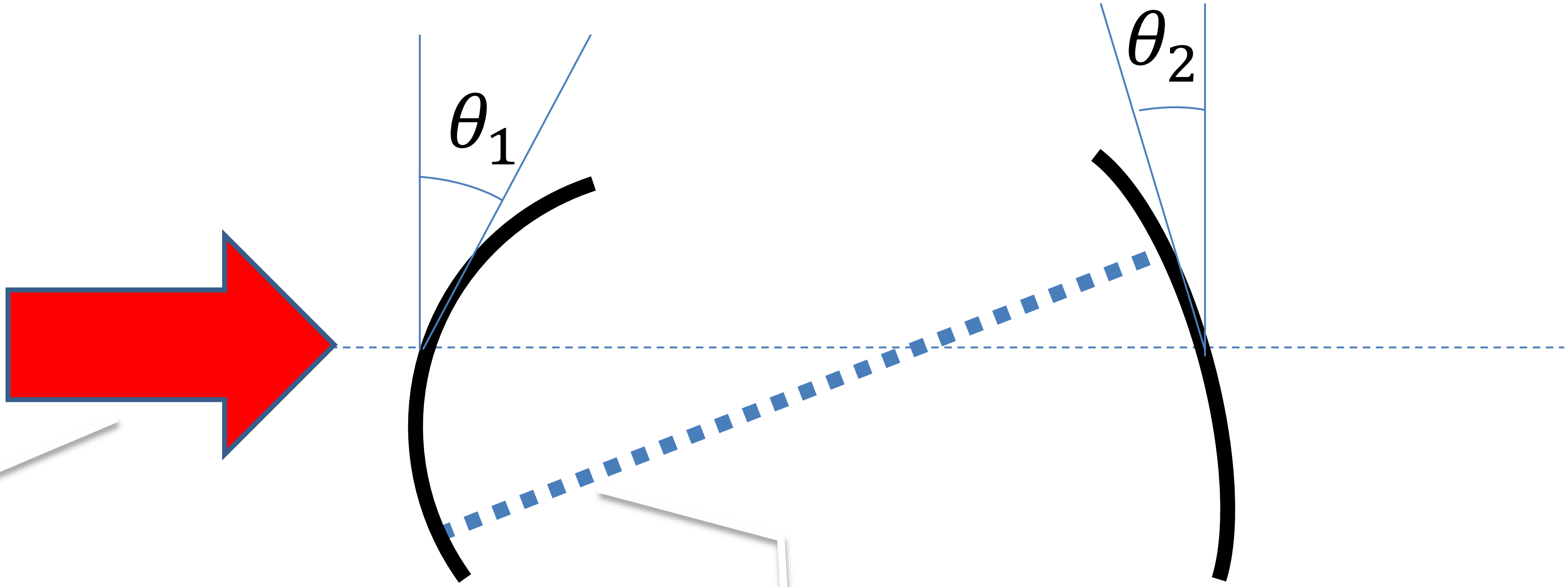
1. Light rays reflect multiple times.
2. Standing wave

Plane-Concave Cavities



1. Light rays reflect multiple times.
2. Standing wave
3. Input beam axis
4. Cavity axis is tilted and offset respect to input

In General:
Two Reference Frames



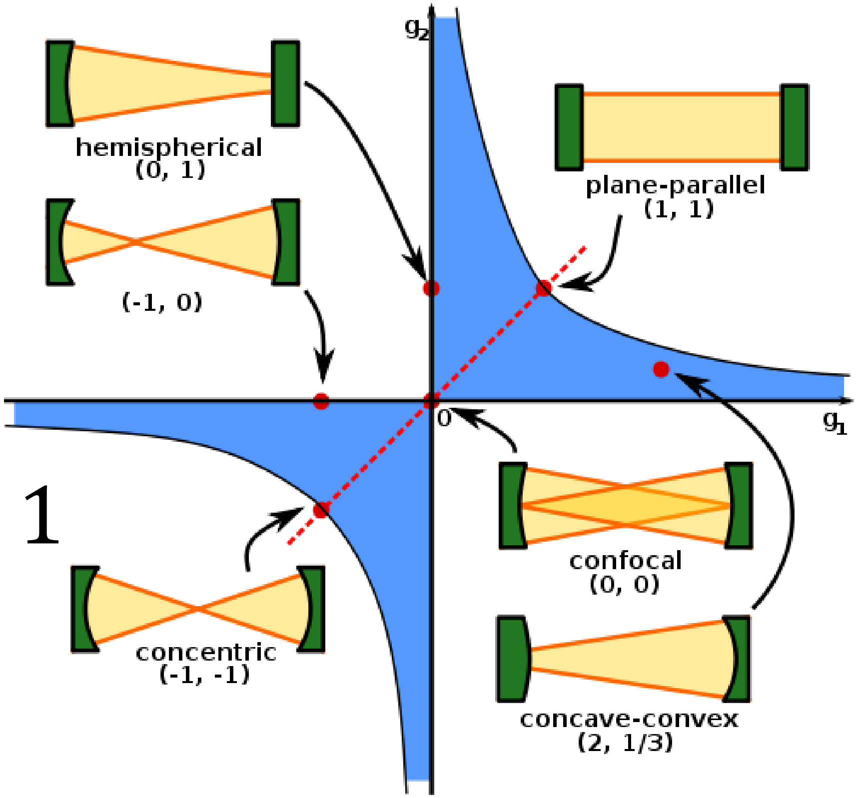
Reference frame of the *input beam axis*

Reference frame of the *cavity axis*: <u>tilted</u> and <u>offset</u> with respect to input beam axis

Stability Condition

$$0 < \left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right) < 1$$

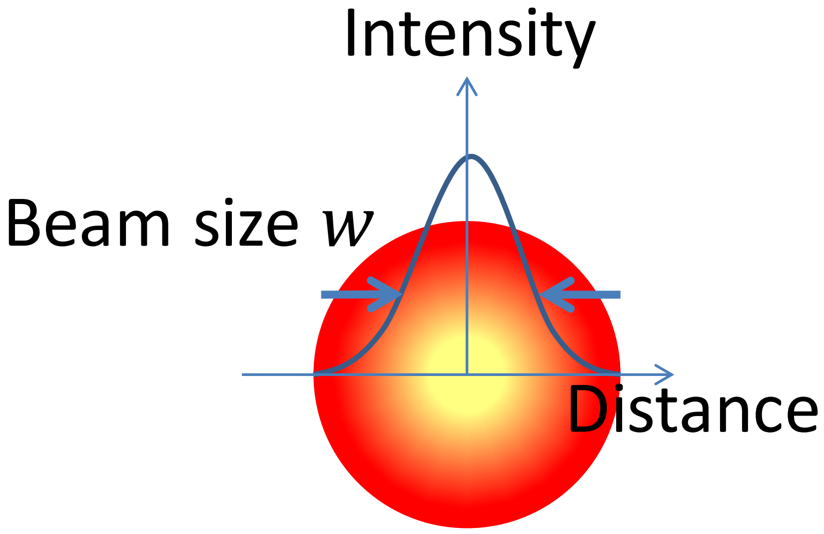
where L is the cavity length and $R_{1,2}$ is the mirror radius of curvature



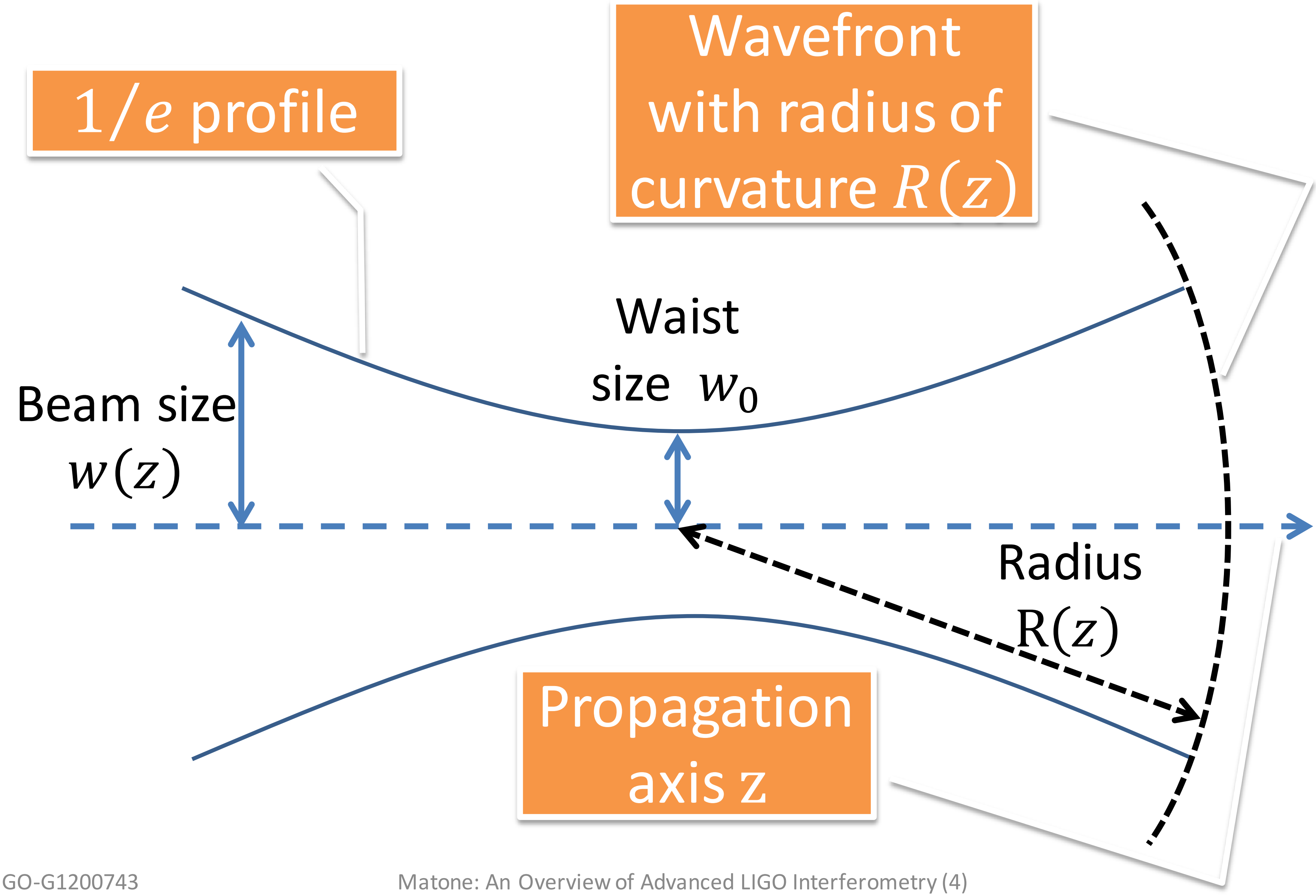
H. Kogelnik and T. Li, *Appl. Opt.* **5**, 1550 (1966)

Laser Beam

- Ideally, coherent light with Gaussian intensity profile
- "Fundamental mode", mostly TEM00
- Beam size w
  - Amplitude decreases by $^1/_e$
  - Gaussian

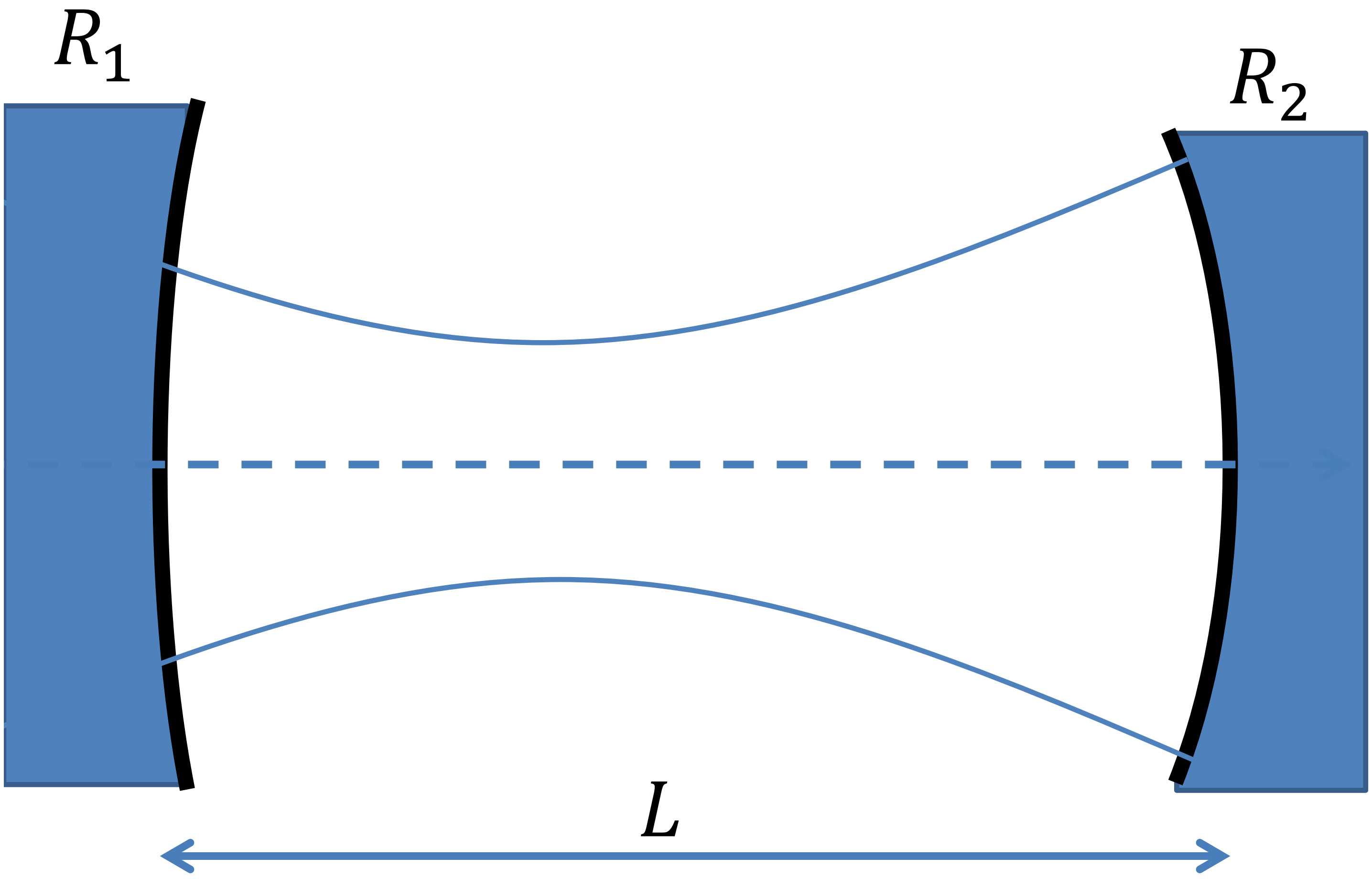


Beam Mode: The Fundamental

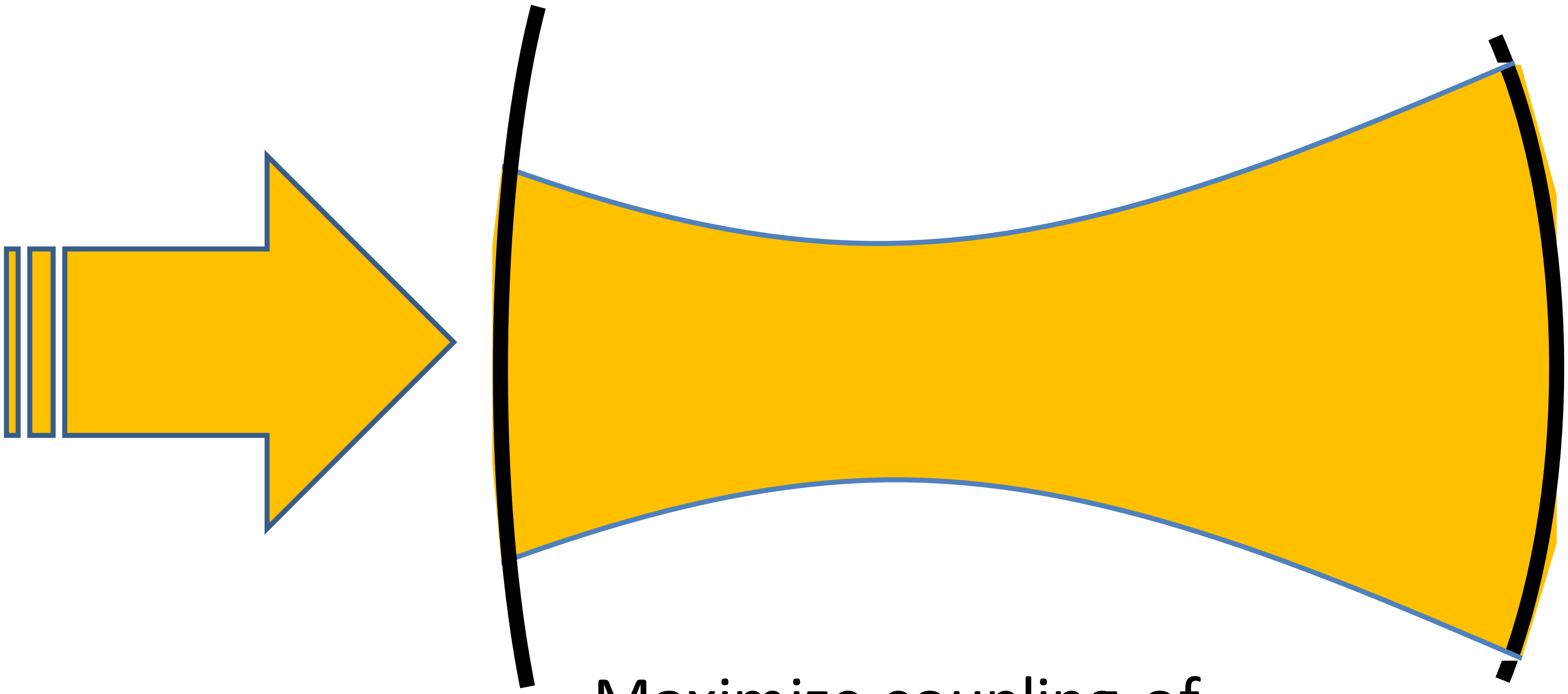


Cavity Mode

The laser mode that would resonate given the cavity geometry (R_1, R_2 and L)



Mode-Matching



Maximize coupling of

<u>the incoming beam mode</u>

to

<u>the cavity mode</u>

Description of a Laser Beam

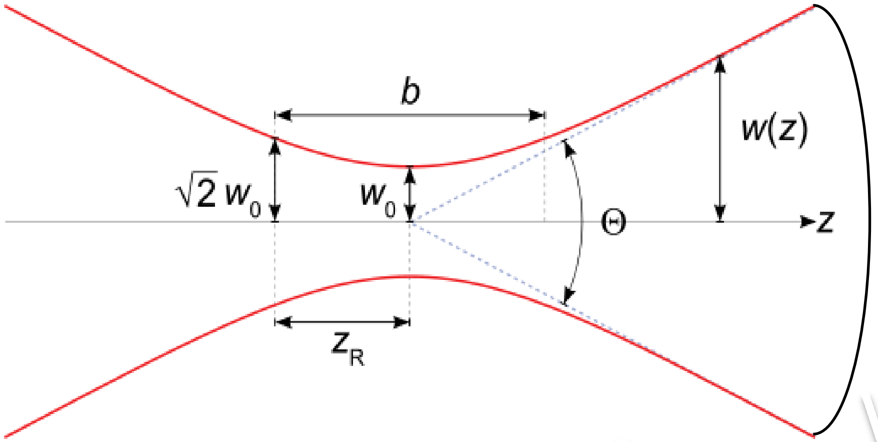
Any laser beam can be represented in terms of TEM (Propagation) modes

Gouy phase

Spot size

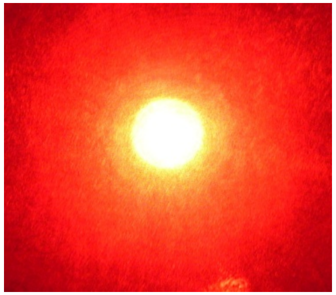
Wavefront radius

$$U_{m,n}(x,y,z) = \frac{A_{m,n}}{w(z)} H_m\left(\sqrt{2}\frac{x}{w(z)}\right) H_n\left(\sqrt{2}\frac{y}{w(z)}\right) \times e^{-(x^2+y^2)/w^2(z)} \times e^{-ik(x^2+y^2)/2R(z)} \times e^{-i\left(kz - \varphi_{m,n}(z)\right)}$$

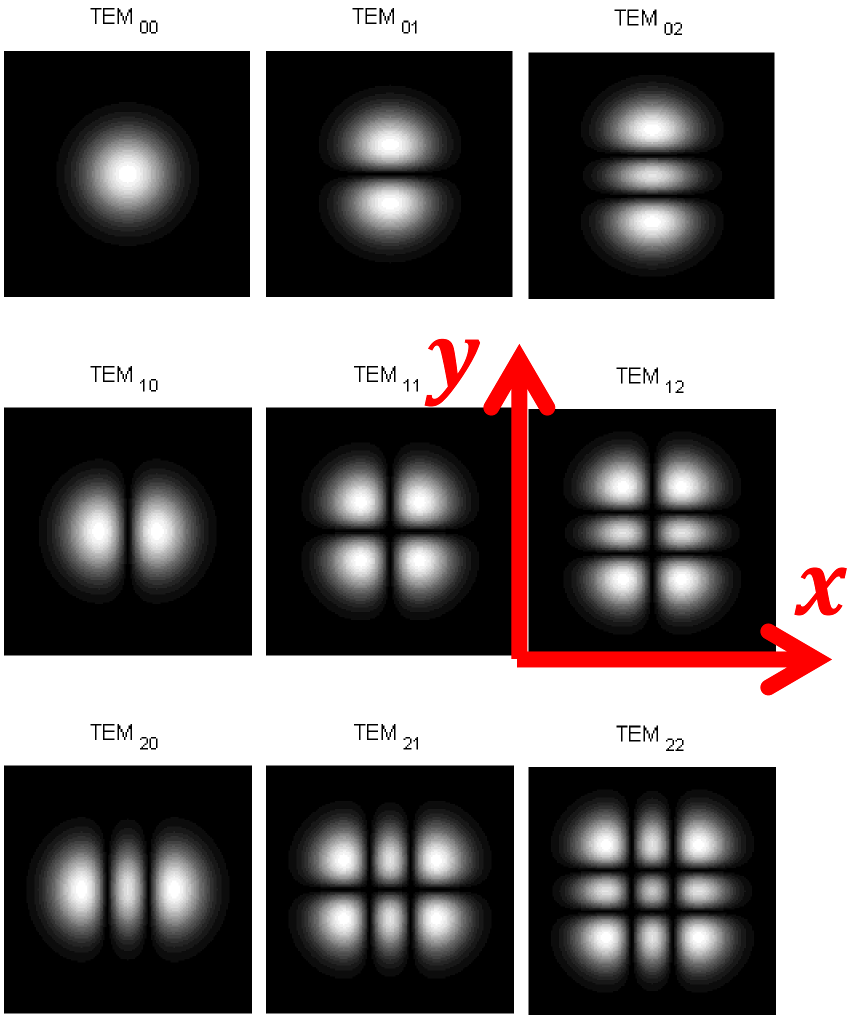


Wavefront

Hermite polynomial



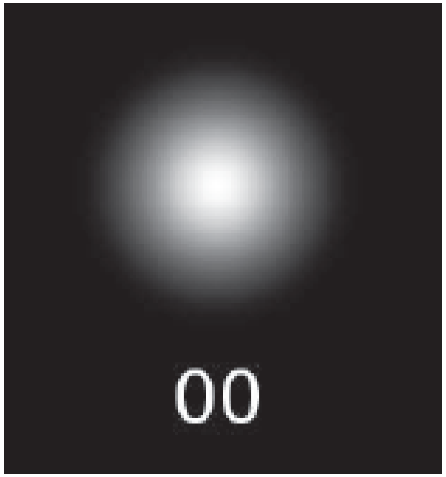
Mode patterns



- TEMmn:
  - Transverse Electro-Magnetic (TEM) modes
- Figure
  - plot of $|U_{m,n}(x,y,z)|^2$ vs. position x, y

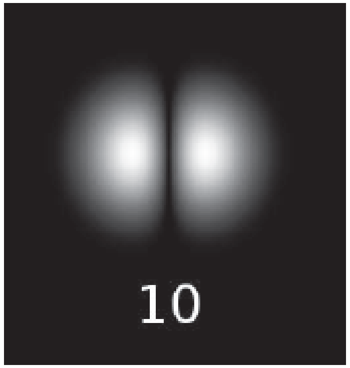
Fundamental Mode: TEM00

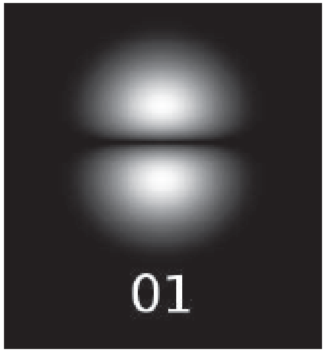
$$U_{0,0}(x,y,z) = \frac{A_{0,0}}{w(z)} \times e^{-\left(x^2+y^2\right)/w^2(z)} \times e^{-ik\left(x^2+y^2\right)/2\,R(z)} \times e^{-i\left(k\,z-\varphi_{0,0}(z)\right)}$$



First order modes: TEM01 and TEM10

$$U_{1,0}(x,y,z) = \frac{A_{1,0}}{w(z)} \times \sqrt{2}\,\frac{x}{w(z)} \times$$
$$e^{-\left(x^2+y^2\right)/w^2(z)} \times$$
$$e^{-ik\left(x^2+y^2\right)/2\,R(z)} \times$$
$$e^{-i\left(k\,z-\varphi_{1,0}(z)\right)}$$





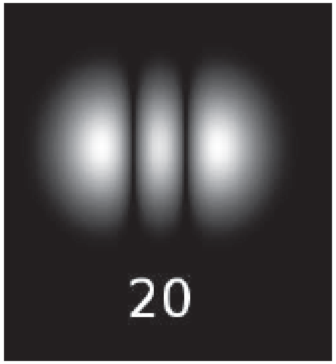
TEM11, TEM20 and TEM02

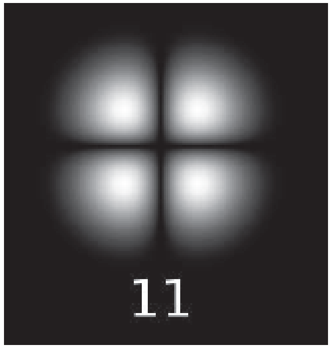
$$U_{1,1}(x,y,z) = \frac{A_{1,1}}{w(z)} \times \sqrt{2}\frac{x}{w(z)} \times \sqrt{2}\frac{y}{w(z)} \times$$

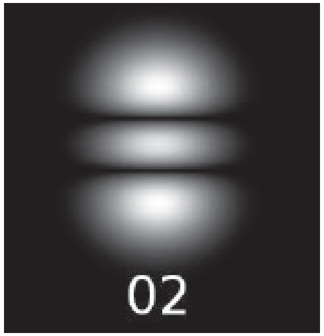
$$e^{-\left(x^2+y^2\right)/w^2(z)} \times$$

$$e^{-ik\left(x^2+y^2\right)/2\,R(z)} \times$$

$$e^{-i\left(k\,z-\varphi_{1,1}(z)\right)}$$







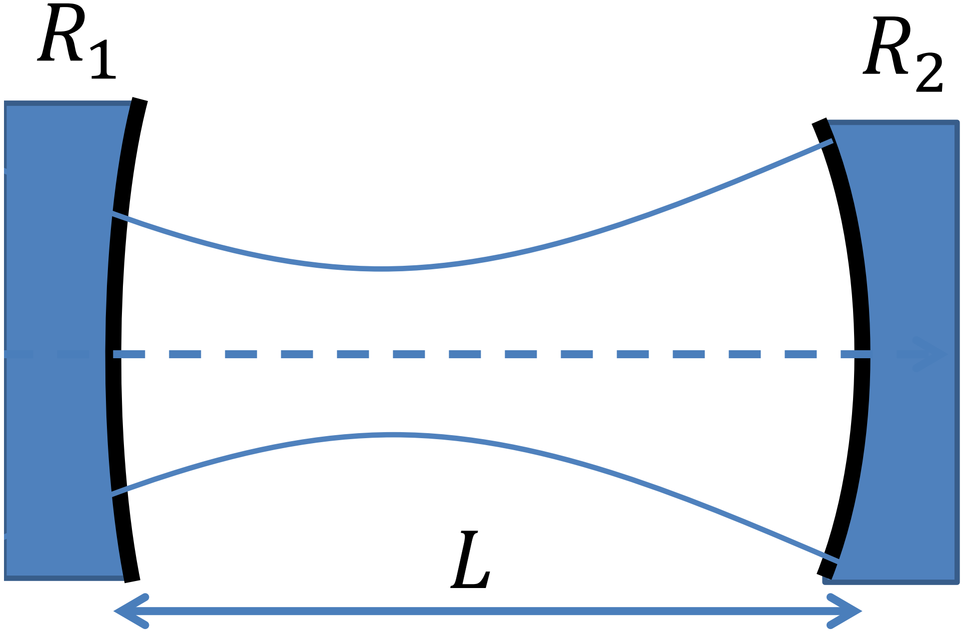
Resonance Condition

TEMmn resonance frequency

Free spectral range (FSR)

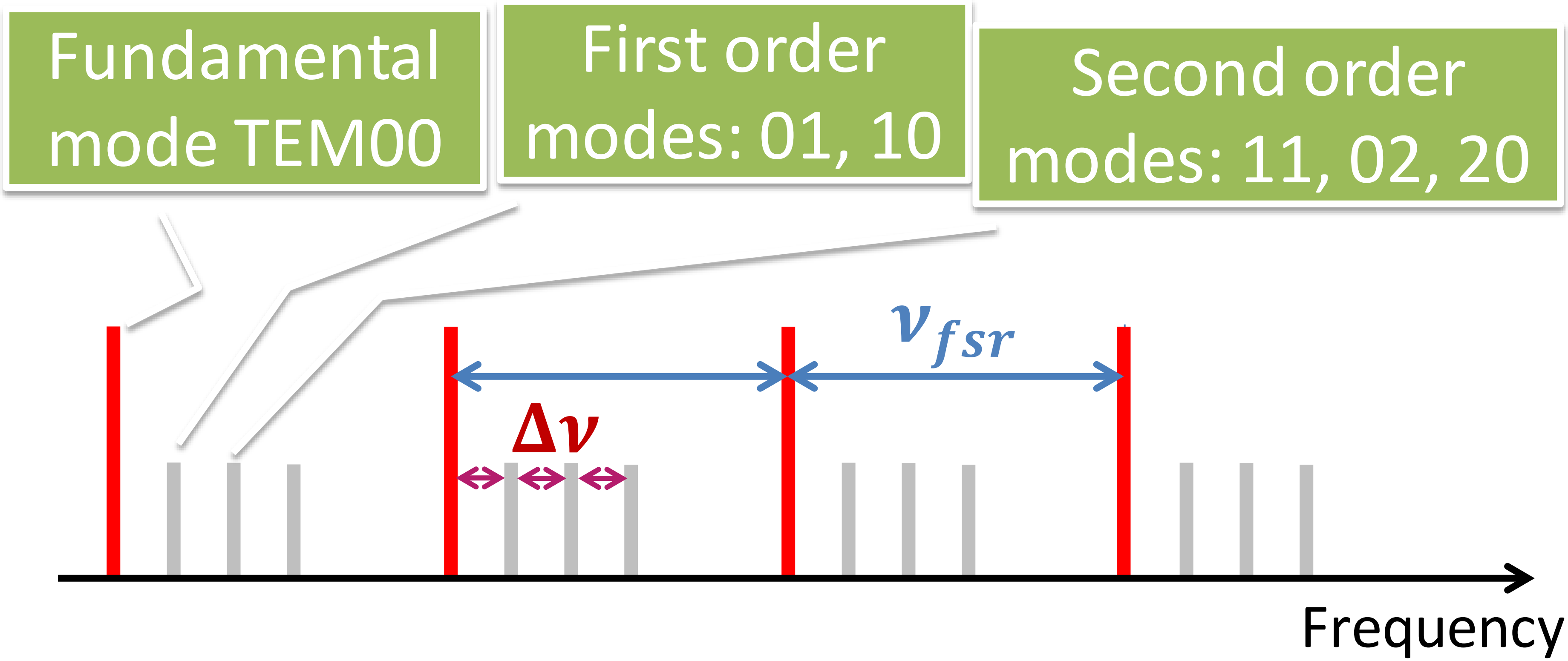
Integer

$$\frac{\nu_{m,n}}{\nu_{fsr}} = (q+1) + \frac{1}{\pi}(m+n+1)\ \cos^{-1}\sqrt{\left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right)}$$

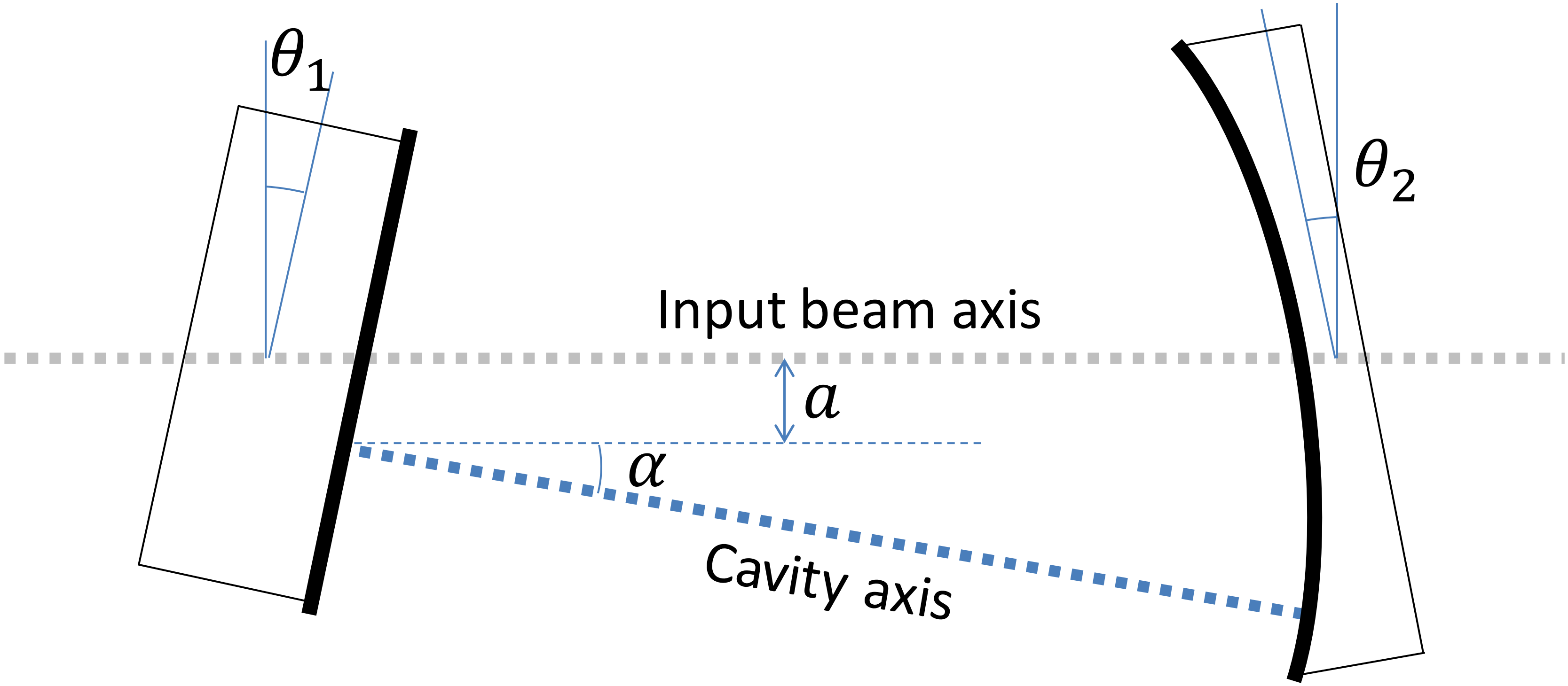


H. Kogelnik and T. Li, *Appl. Opt.* **5**, 1550 (1966)

Transverse Mode Spacing $\Delta\nu$

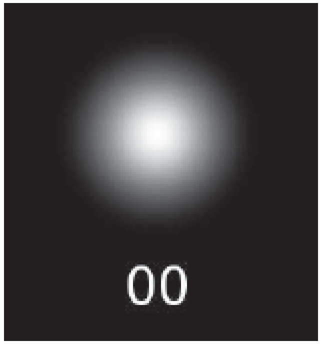


$$\frac{\Delta\nu}{\nu_{fsr}} = \frac{1}{\pi}\cos^{-1}\sqrt{\left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right)}$$

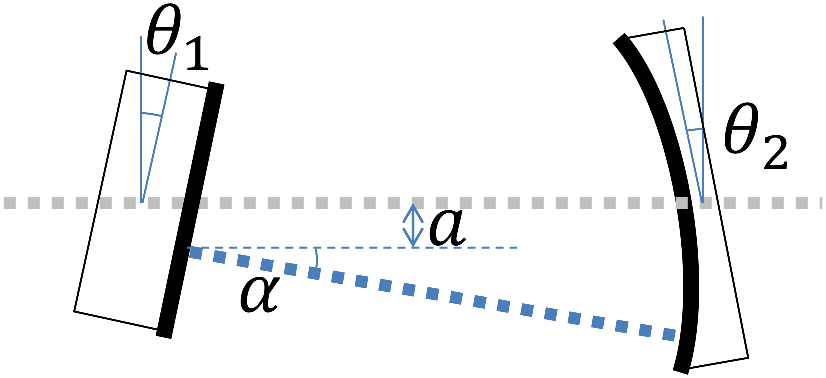


Cavity axis is translated and tilted by a and α with respect to the input beam axis.

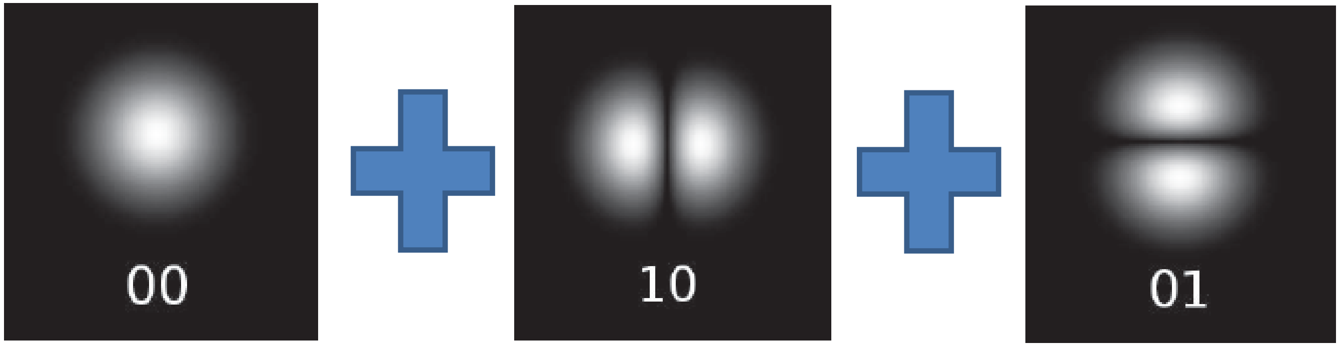
If a and α are “small” then to first order approximation



Input



Output



Aligned Cavity

$\psi_{in} = U_{0,0}$

Input

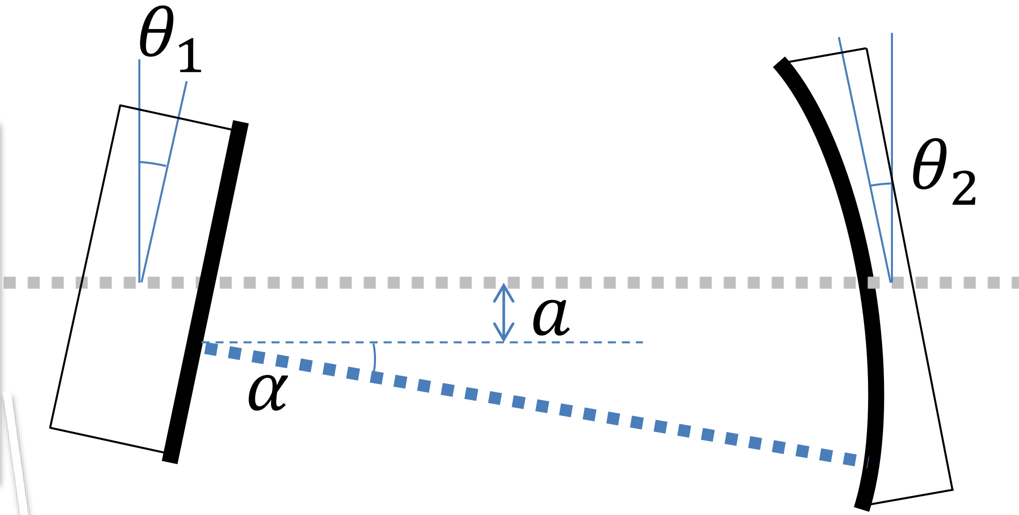
Output

$\psi_{refl} = \mathcal{R}_{0,0} U_{0,0}$

Misaligned Cavity

$$\psi_{in} = U_{0,0}$$

Input



The amount of TEM01 tells you how the cavity is misaligned

Output

$$\psi_{refl} = \mathcal{R}_{0,0} U_{0,0} + \boxed{(a + i\alpha)} \mathcal{R}_{0,1}\, U_{0,1}$$

Measuring Misalignments

- Modulating incoming laser field so that sidebands do not resonate in cavity
- Demodulating on reflection

$$\psi_{in} = J_0 U_{00} + J_1 U_{00} e^{i\,\Omega\,t} - J_1 U_{00} e^{-i\,\Omega\,t}$$

$$\psi_{refl} = \psi_{refl,0} + \psi_{refl,+}\, e^{i\,\Omega\,t} + \psi_{refl,-}\, e^{-i\,\Omega\,t}$$

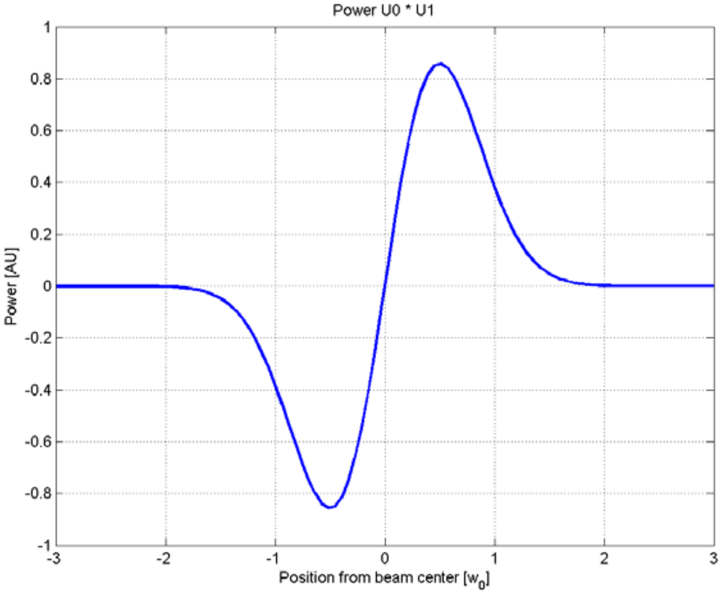
Mixing determined by Gouy phase φ_{00}

$$\left|\psi_{refl}\right|^2 = \mathrm{DC} + \boxed{J_0 J_1 U_{00} U_{01} (\alpha \cos\varphi_{00} + i\ a \sin\varphi_{00})}\ \sin\Omega t$$

Inphase demodulated signal contains misalignment information

Morrison E. et al., *Appl. Opt.* **33**, 5037-5040 (1994)

How? Wavefront Sensor



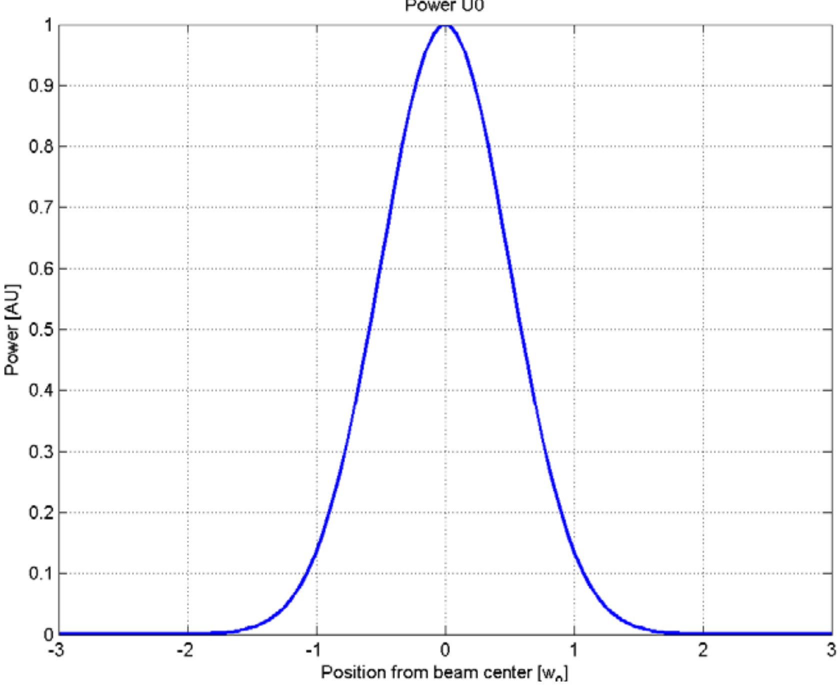
- Plot of $U_{00}U_{01}$ vs. position from beam axis.
  - Recall that the demodulated signal is

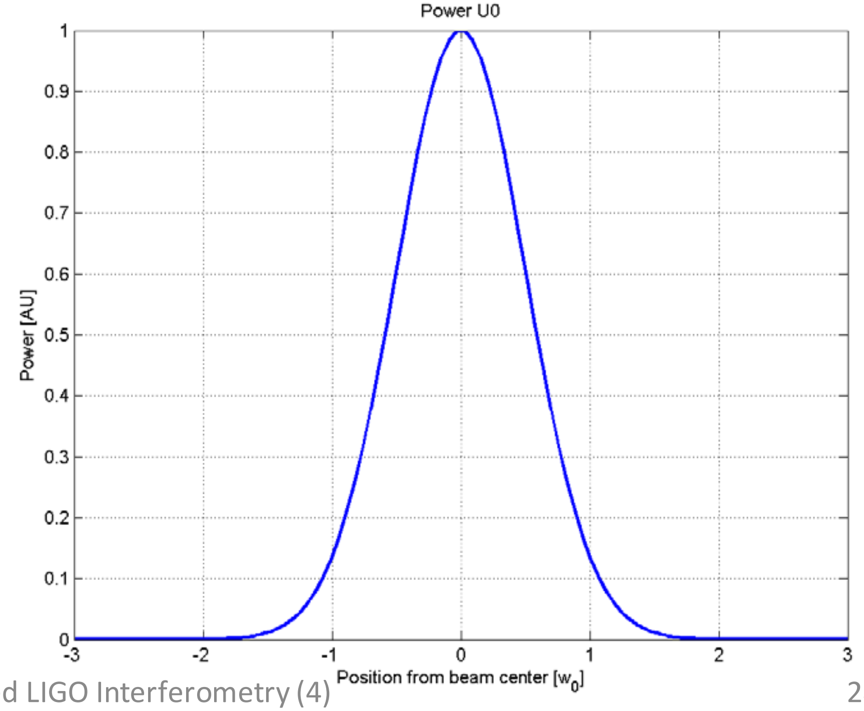
$$J_0 J_1 \boxed{U_{00}U_{01}}(\alpha \cos\varphi_{00} + i\, a \sin\varphi_{00})$$

- To measure $U_{00}U_{01}$ we need a special photodiode
  - $U_{00}U_{01}$ is an odd function (anti-symmetric) about the beam axis
  - A ‘standard’ photodetector would integrate over the beam surface and measure zero.
- Need a special photodiode: Wavefront Sensor

TEM00 example

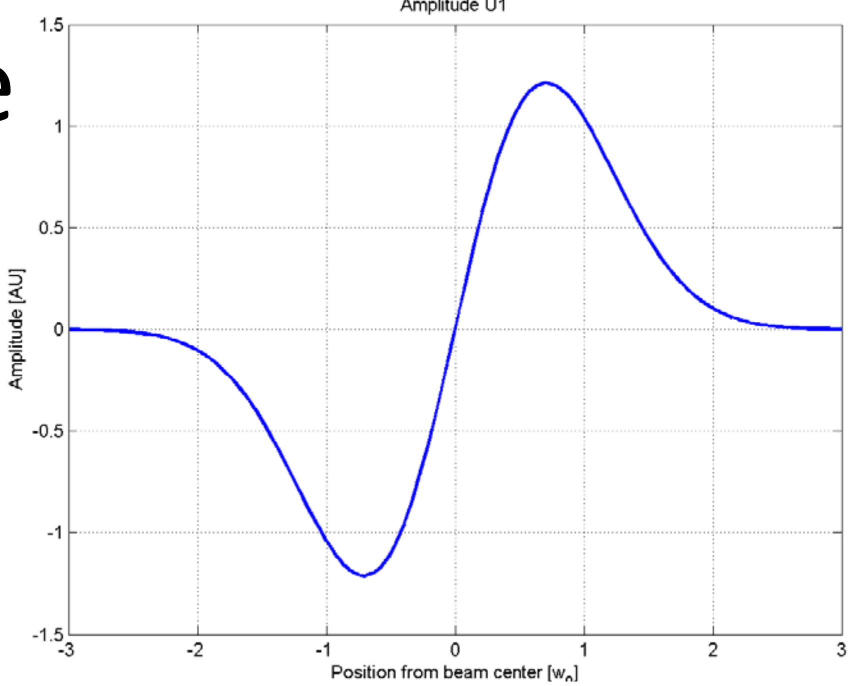
- Plot of TEM00 vs. position from beam axis
- Plot of TEM00 power vs. position from beam axis
- Photodetector would integrate over beam profile (area under the curve) to measure beam power: non-zero measure

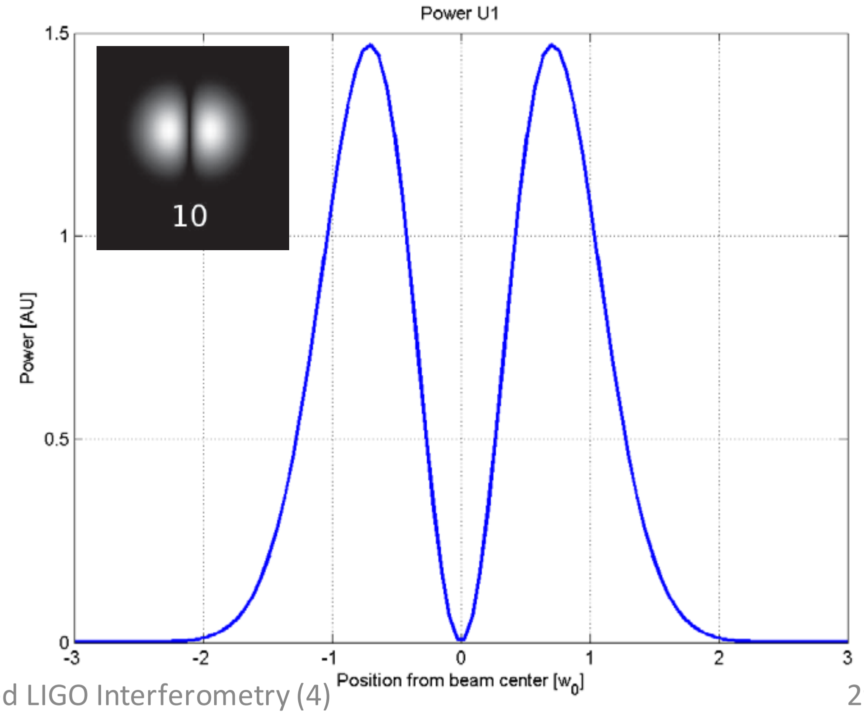




TEM01 example

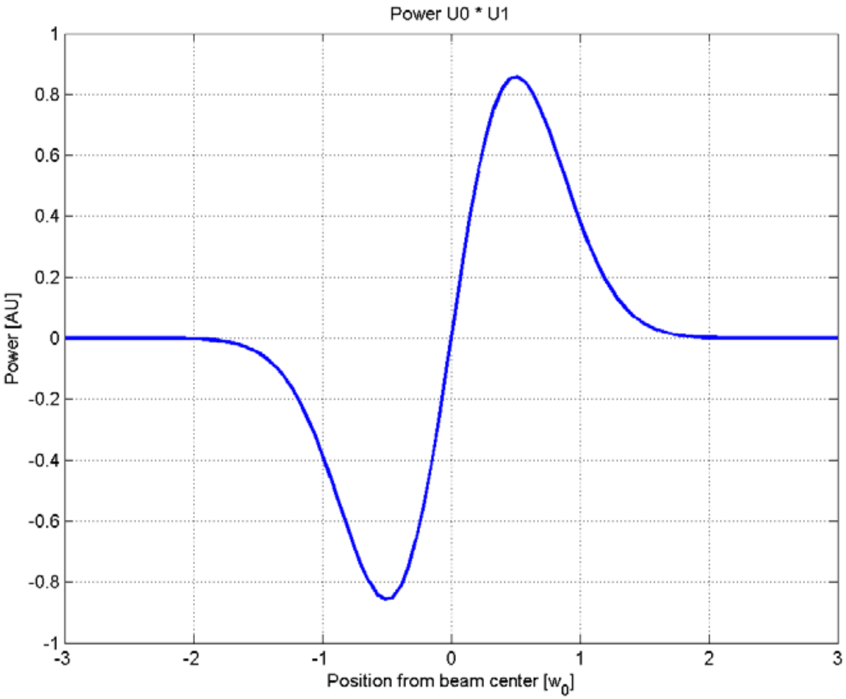
- Plot of TEM01 vs. position from beam axis
- Plot of TEM01 power vs. position from beam axis
- Photodetector would integrate over beam profile (area under the curve) to measure beam power: non-zero measure
- No information given about the presence of "lobes"





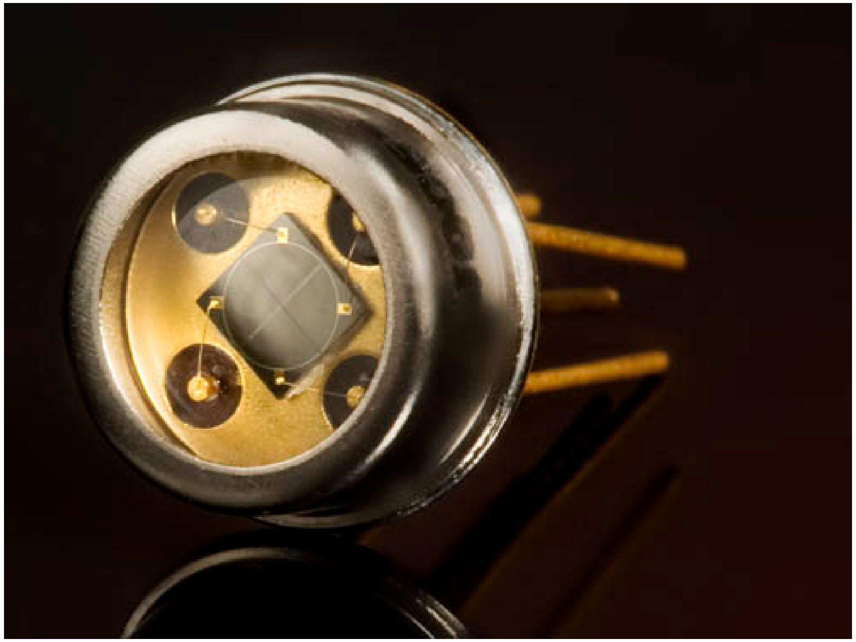
TEM00 * TEM01

- Plot of TEM00 * TEM01 vs. position from beam axis
- Odd function about the beam axis
- Photodetector would integrate over beam profile (area under the curve) to measure beam power: zero measure
- Complete loss of information



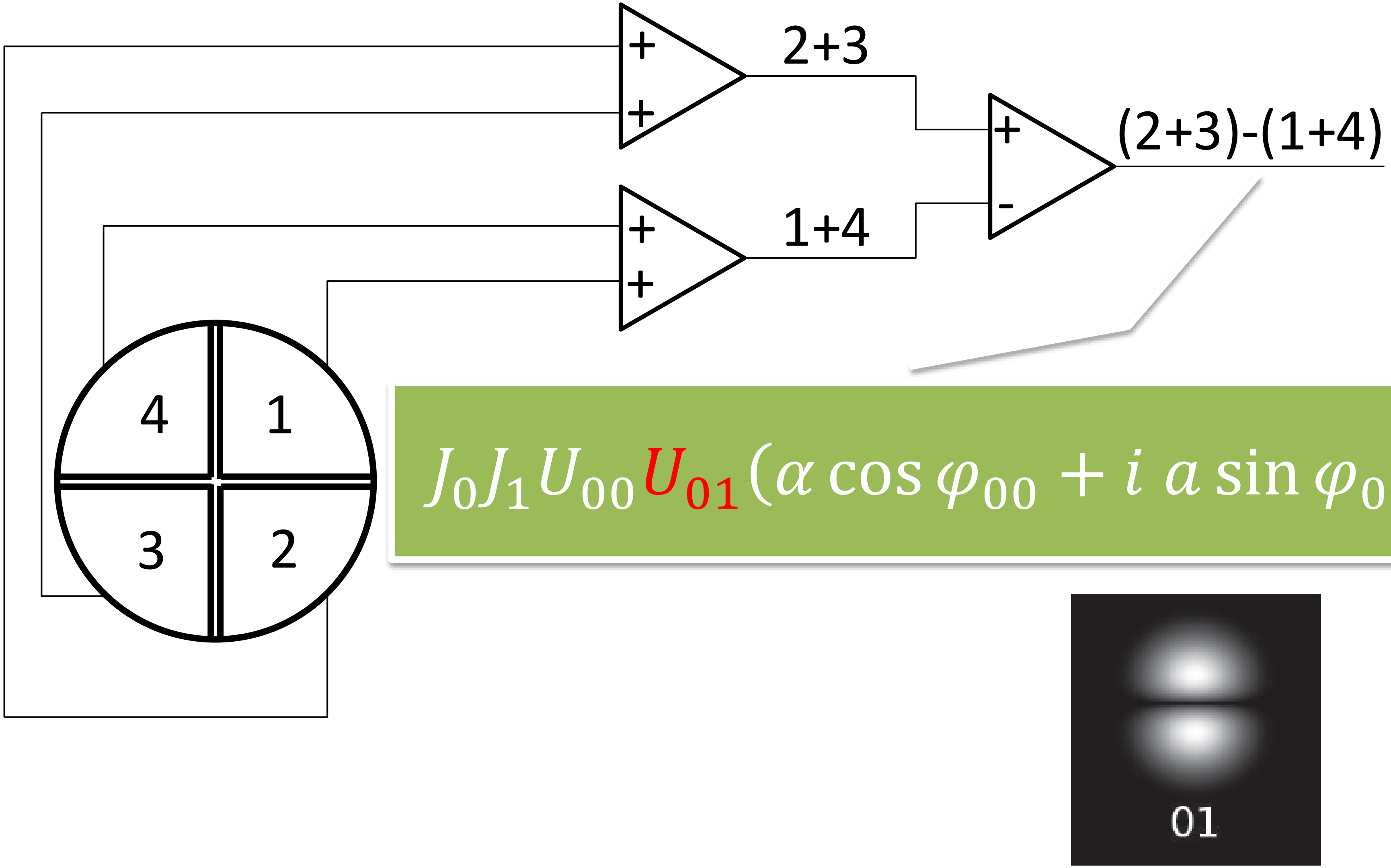
Wavefront Sensor

- Able to integrate half-plane (or quarters)
- Sum of the signals gives power on the four half planes
- Taking the different between half planes, we recuperate the “lost” signal



$$\int_0^\infty U_{00}(x)\,U_{10}(x)dx \;-\int_{-\infty}^0 U_{00}(x)\,U_{10}(x)dx = \sqrt{\frac{2}{\pi}}$$

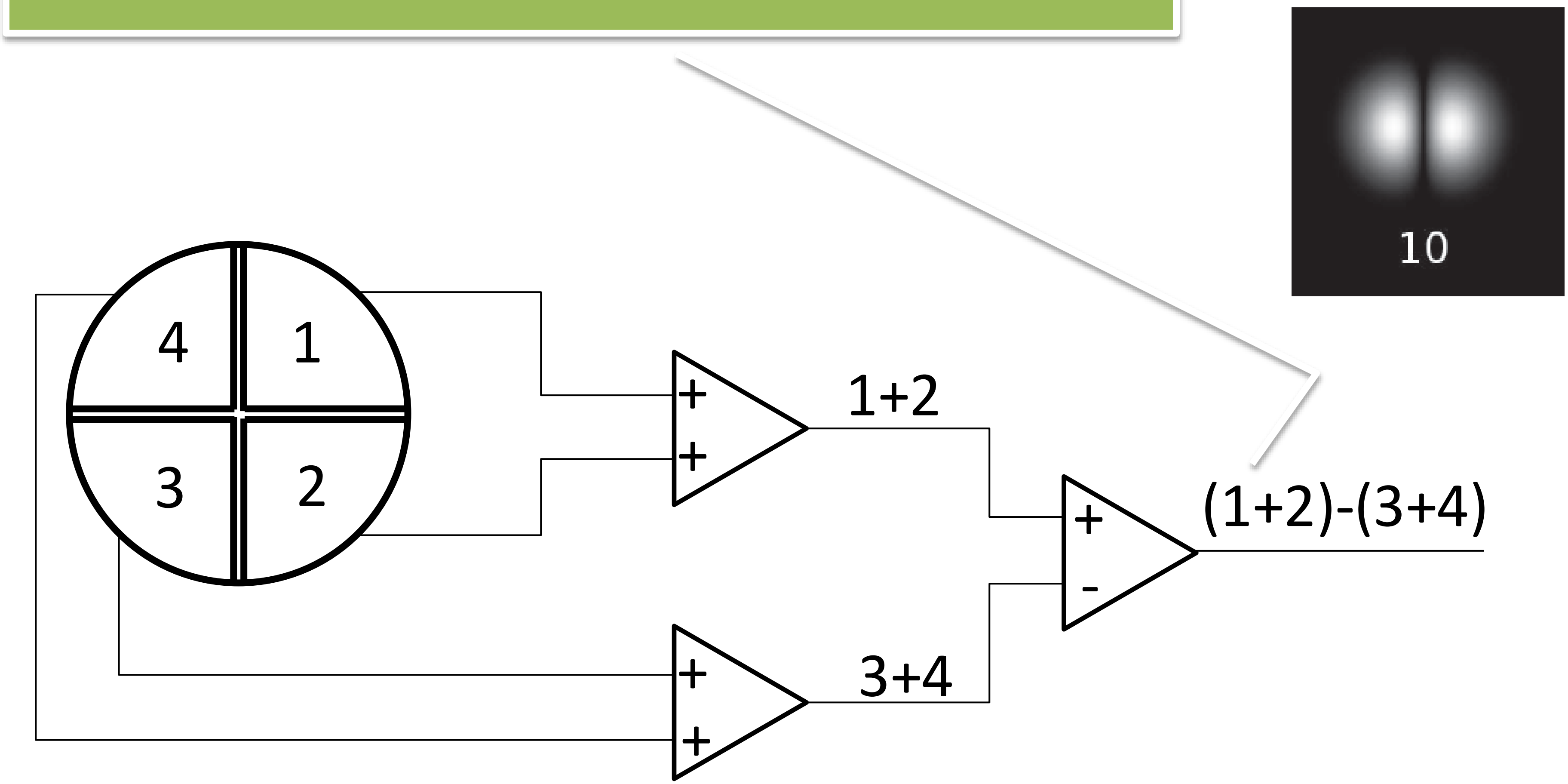
Vertical



$$J_0 J_1 U_{00} U_{01} (\alpha \cos \varphi_{00} + i\, a \sin \varphi_{00})$$

Horizontal

$$J_0 J_1 U_{00} U_{10} (\alpha \cos \varphi_{00} + i\, a \sin \varphi_{00})$$



Gouy Phase

$$J_0 J_1 U_{00} U_{01} (\alpha \cos \varphi_{00} + i\, a \sin \varphi_{00})$$

Gouy phase

$$\varphi_{00} = \tan^{-1}\left(\frac{\lambda\, z}{\pi\, {w_0}^2}\right)$$

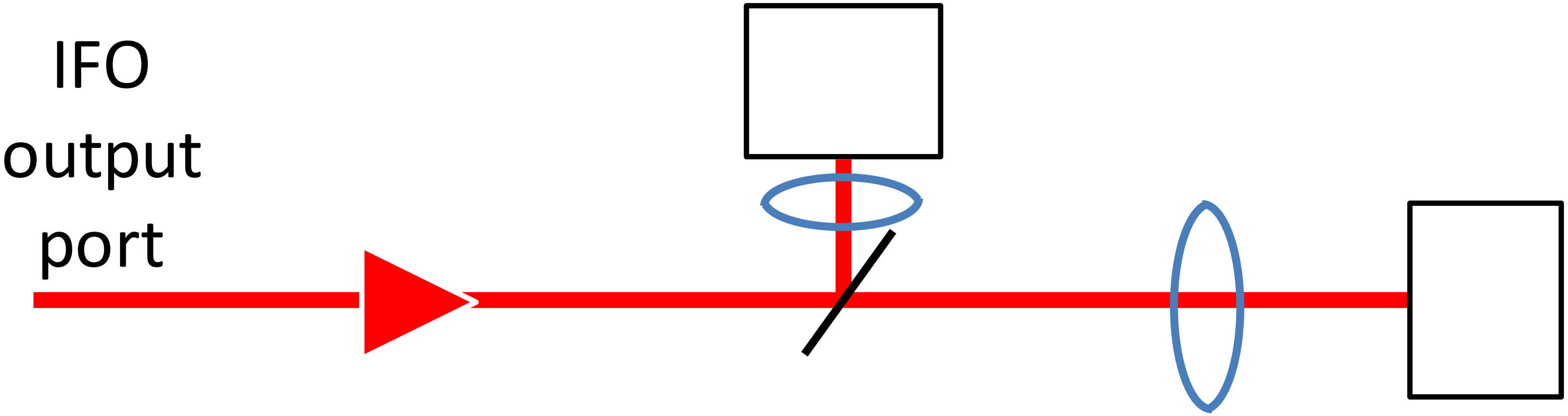
Gouy phase depends on distance z from waist w_0

- $\varphi_{00} = 0$ at the waist
- $\varphi_{00} = \pi/2$ far from the waist

Placing a wavefront sensor at a particular Gouy phase allows you to measure

- just translations a, or
- just tilts α
- or a mix.

Gouy Phase Telescope



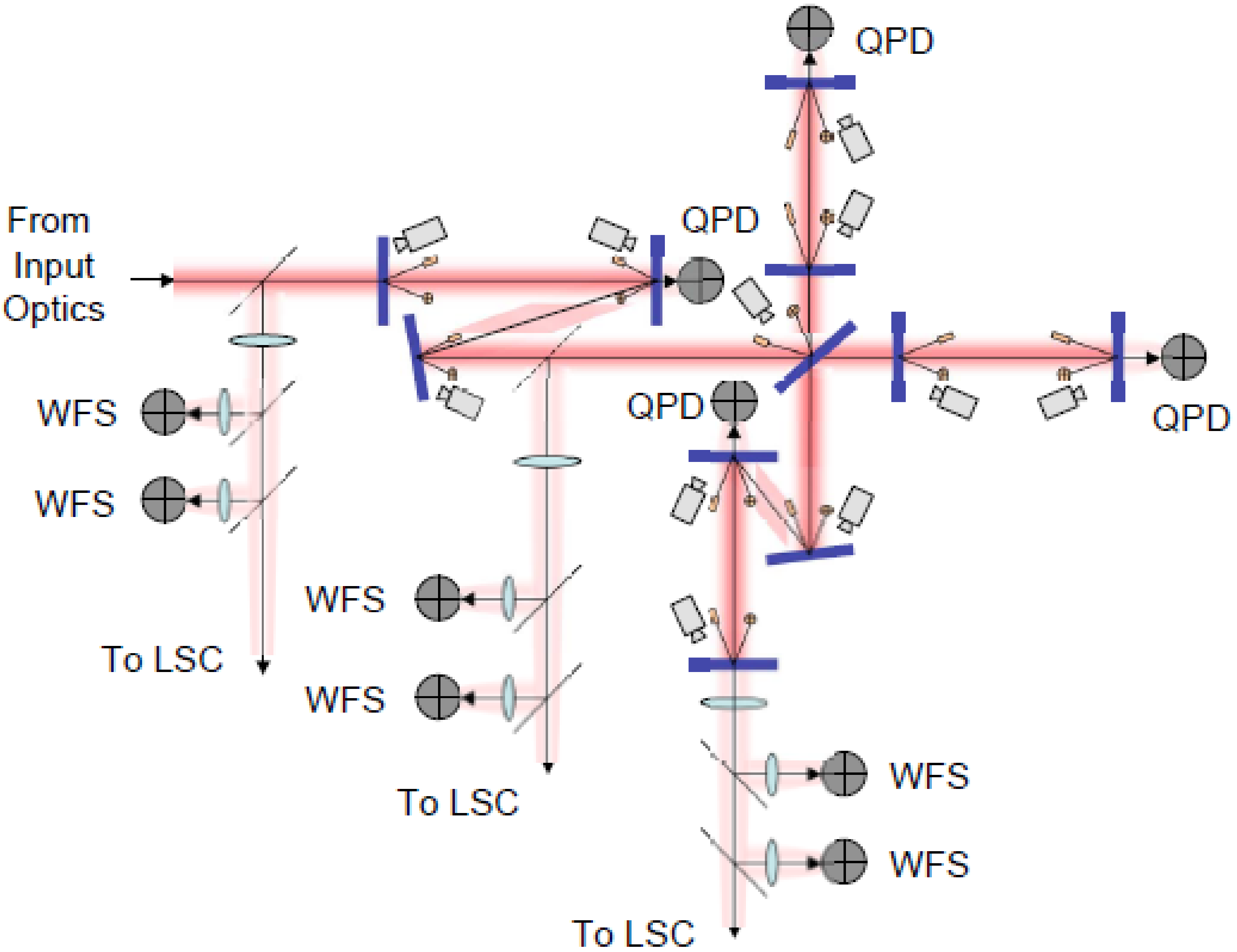
Wavefront sensor
at $\varphi_{00} = 0$

IFO
output
port

Wavefront sensor
at $\varphi_{00} = \pi/2$

One sensor would provide translation information – the other tilt information

Wavefront Sensors in AdvLIGO



From the "AdvLIGO Interferometer Sensing and Control Conceptual Design" T070247

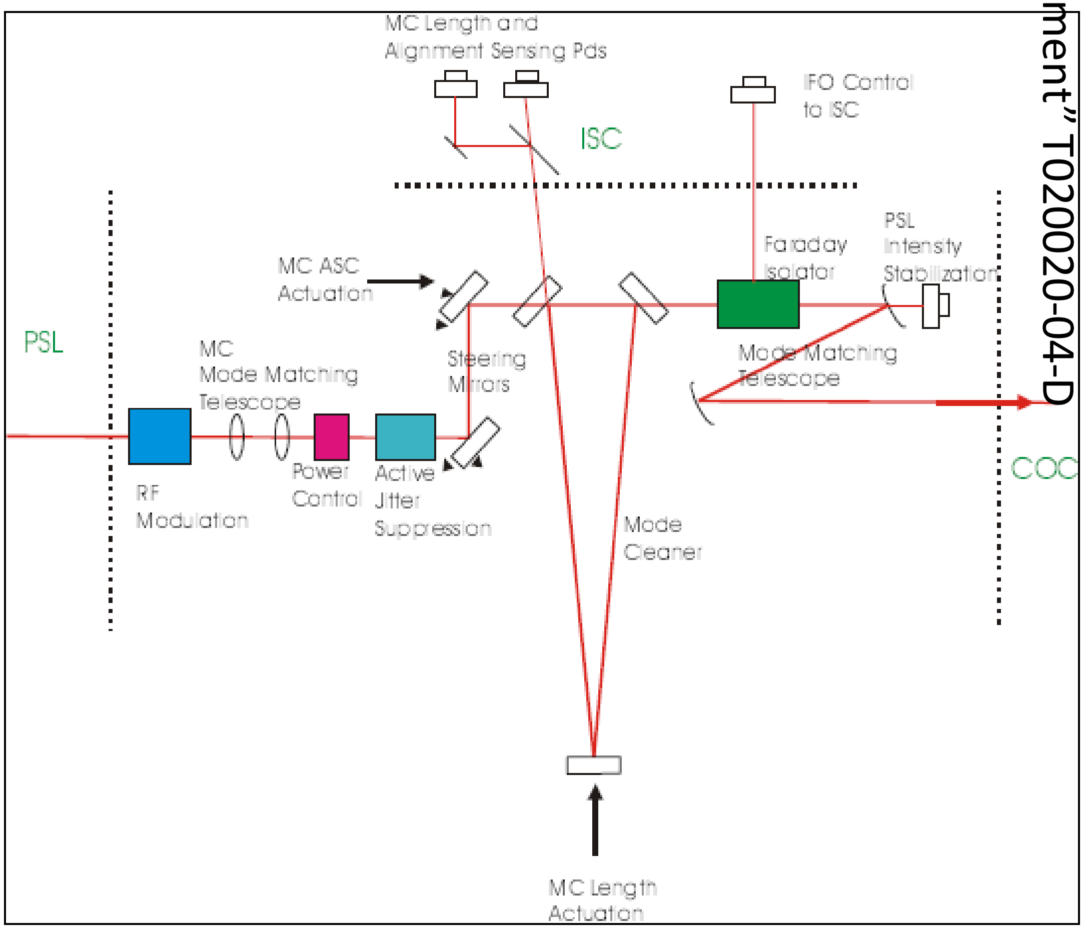
So far…

- TEM
- Cavity Mode and Input Laser Beam
  - Cavity mode: defined by resonator geometry
  - Input laser beam: represented as a linear combination of TEM (mostly 00)
  - Mismatch (mode-mismatch, or misalignments) between the two: generates higher-order TEMs
- Automatic Alignment and Wavefront sensors
  - The amount of first-order TEMs (01 or 10) provides alignment information
  - PDH modulation, sidebands do not resonate in cavity
  - Wavefront sensors placed at two Gouy phases
  - Sensing Matrix

The Input Mode-Cleaner

Triangular cavity

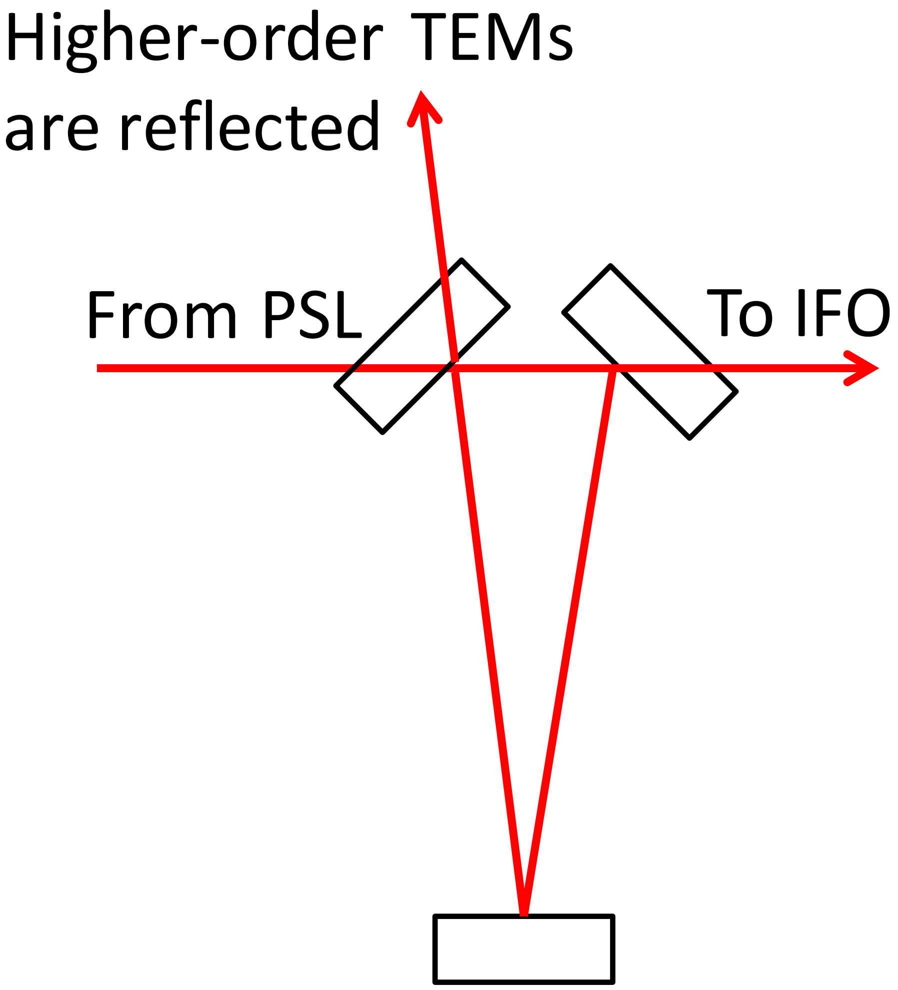
1. Spatially filters incoming laser beam
2. Provides frequency noise suppression
3. Attenuates laser beam jitter



From the "Input Optics Subsystem Design Requirements Document" T020020-04-D

Spatial filtering

- Incoming beam
  - Beam defects (higher order TEMs) are reflected (rejected)
  - Only fundamental mode (TEM00) resonates in cavity and is completely transmitted



Frequency Stabilization

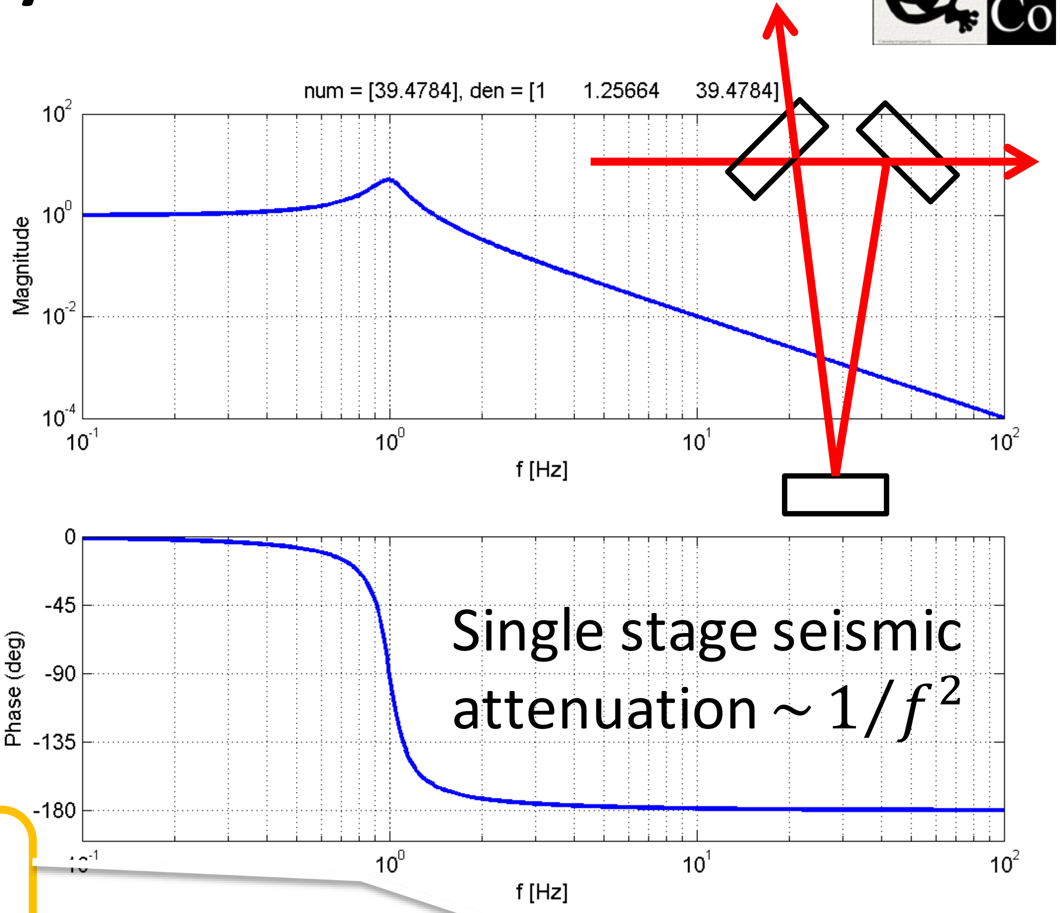
- Cavity used as frequency standard (for high frequencies)
- Let L be the MC length (with ΔL length fluctuations) and ν the laser frequency (with $\Delta\nu$ fluctuations) then

$$\frac{\Delta L}{L} = \frac{\Delta\nu}{\nu} \quad \Rightarrow \boxed{\Delta\nu = \nu\,\frac{\Delta L}{L}}$$

Smaller residual frequency fluctuations $\Delta\nu$

Big $(17\,m)$

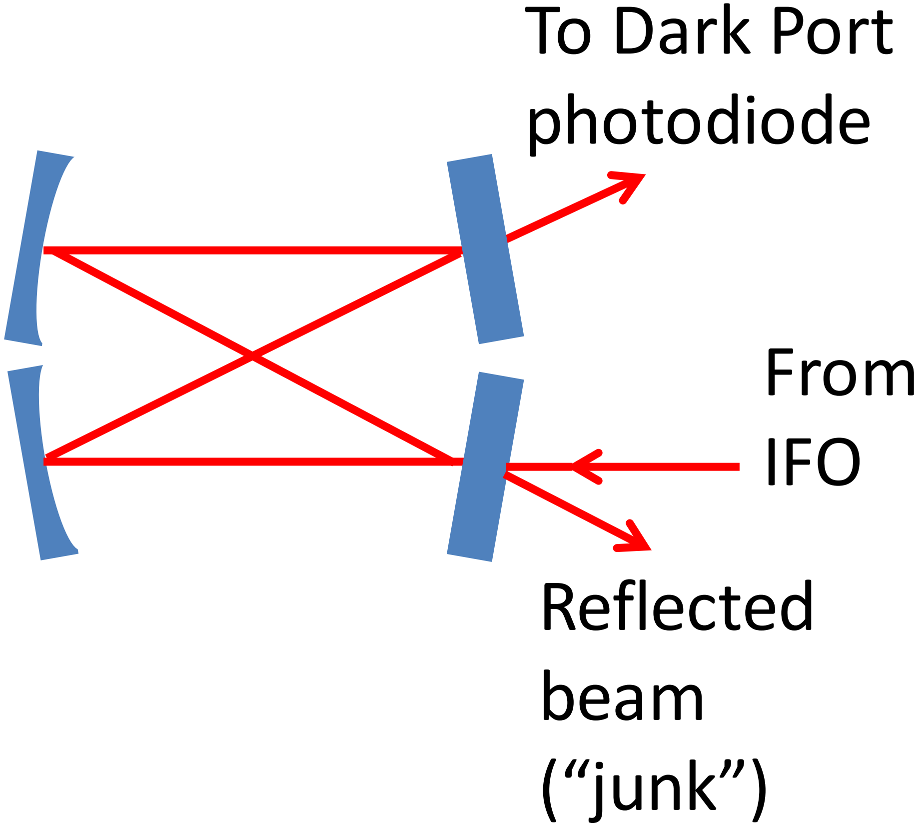
Small ΔL



Single stage seismic attenuation $\sim 1/f^2$

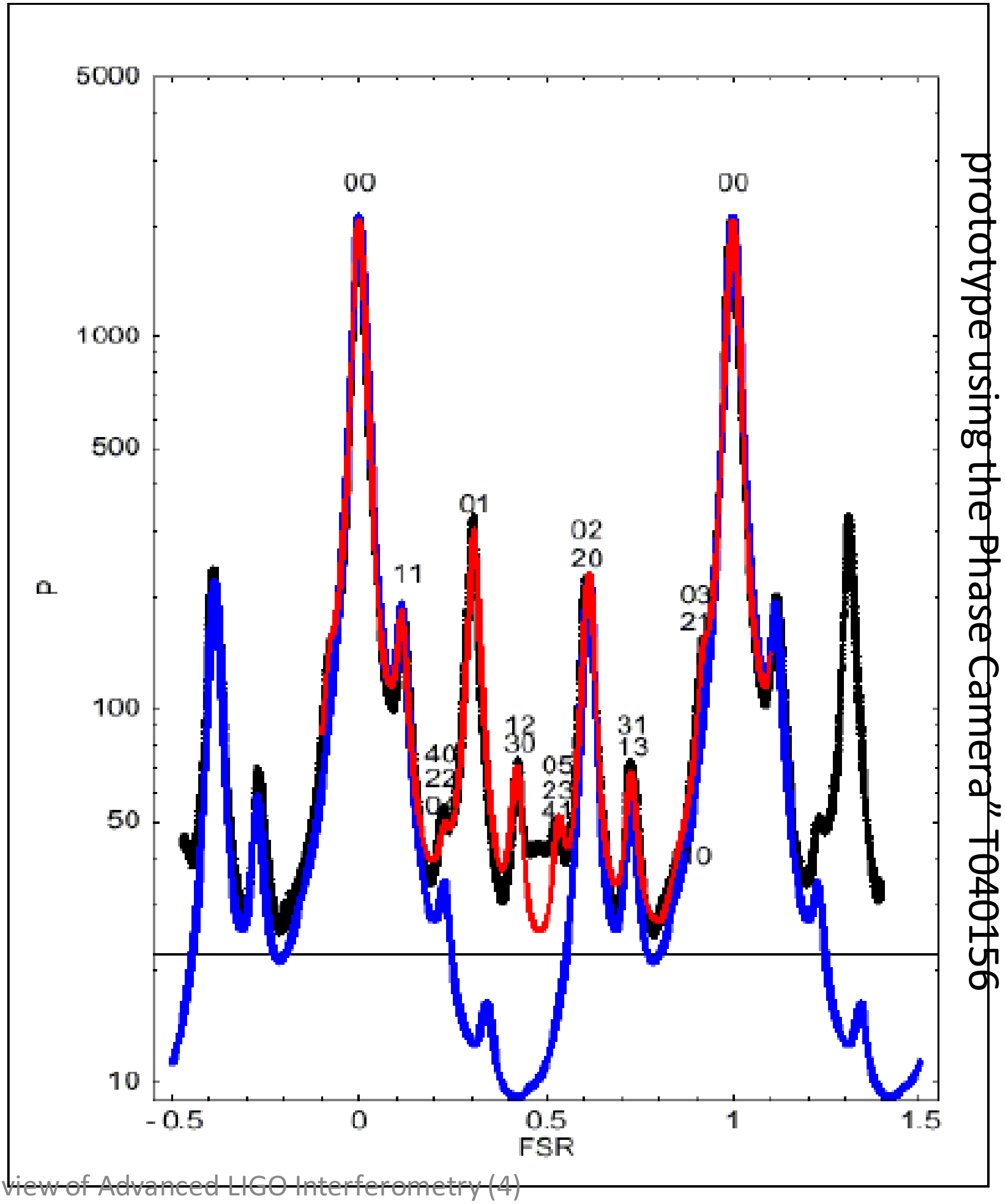
Output Mode-Cleaner (OMC)

- Four-mirror bow tie configuration
- Homodyne detection
  - Carrier TEM00 carries GW information
- OMC filters out RF sidebands
- OMC filters out all non-TEM00 modes ("junk" light)
- IFO's wavefront deformation due to
  - Imperfections in the optical components and their deformation under heating.



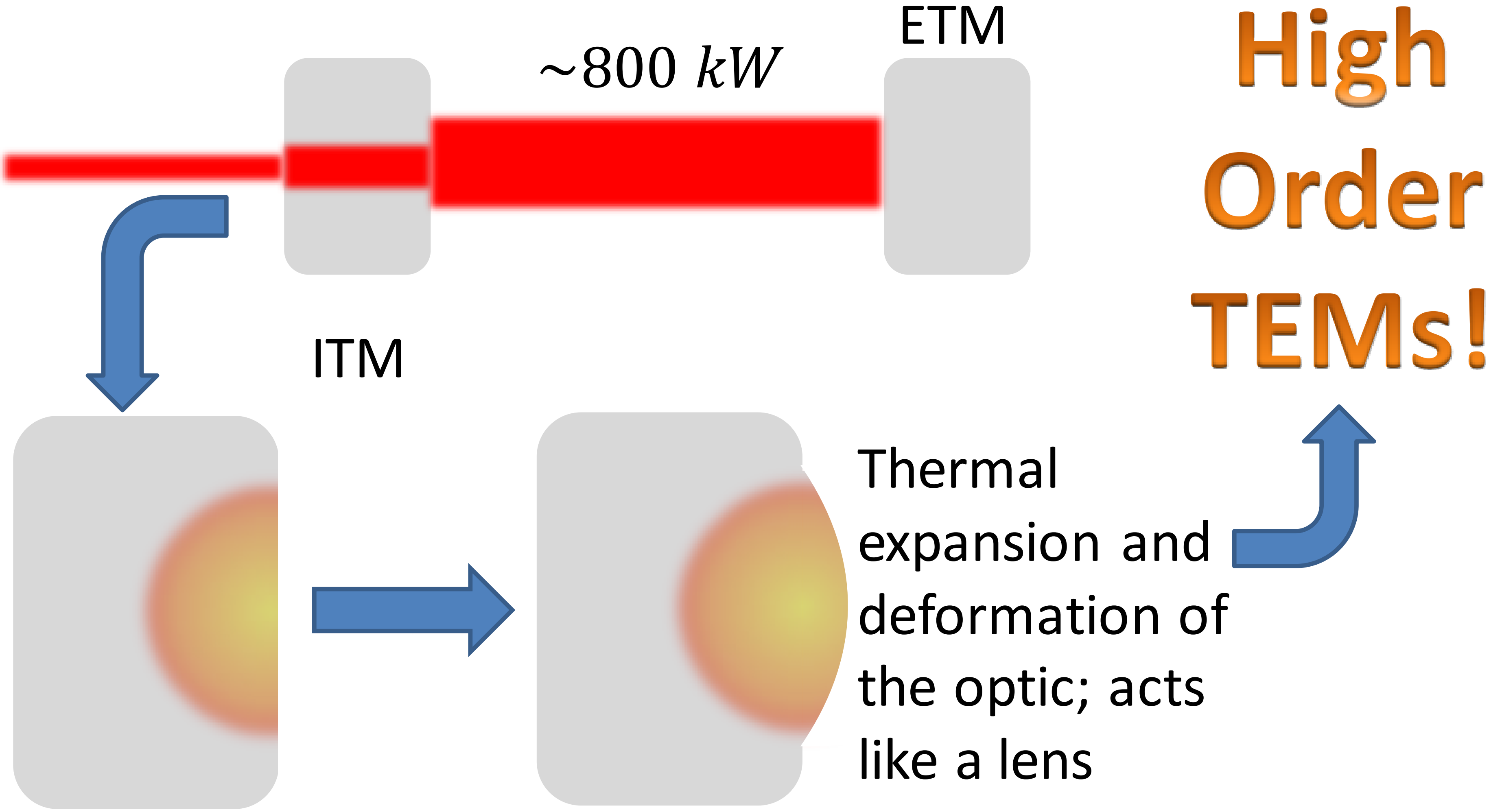
OMC length scan (old data)

- Plot of OMC transmitted power vs cavity length
- Presence of high order modes
- Black – data, blue – model, red – fit



From Keita Kawabe "Study of the OMC prototype using the Phase Camera" T040156

Power absorbed and thermal deformations

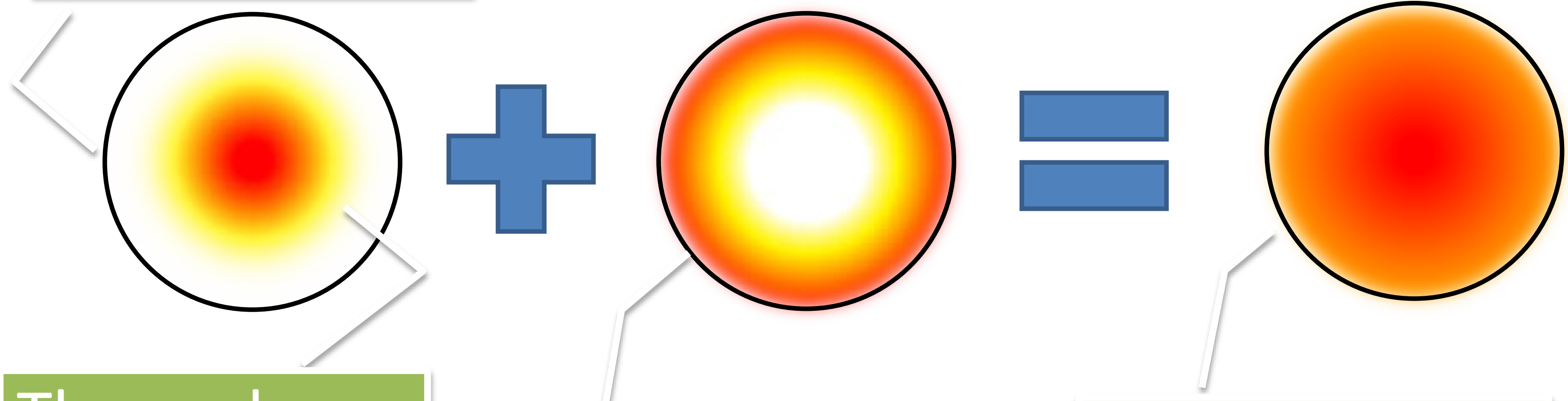


High Order TEMs!

Thermal expansion and deformation of the optic; acts like a lens

Thermal absorption leads to …

Thermal Compensation System (TCS): compensate for deformations



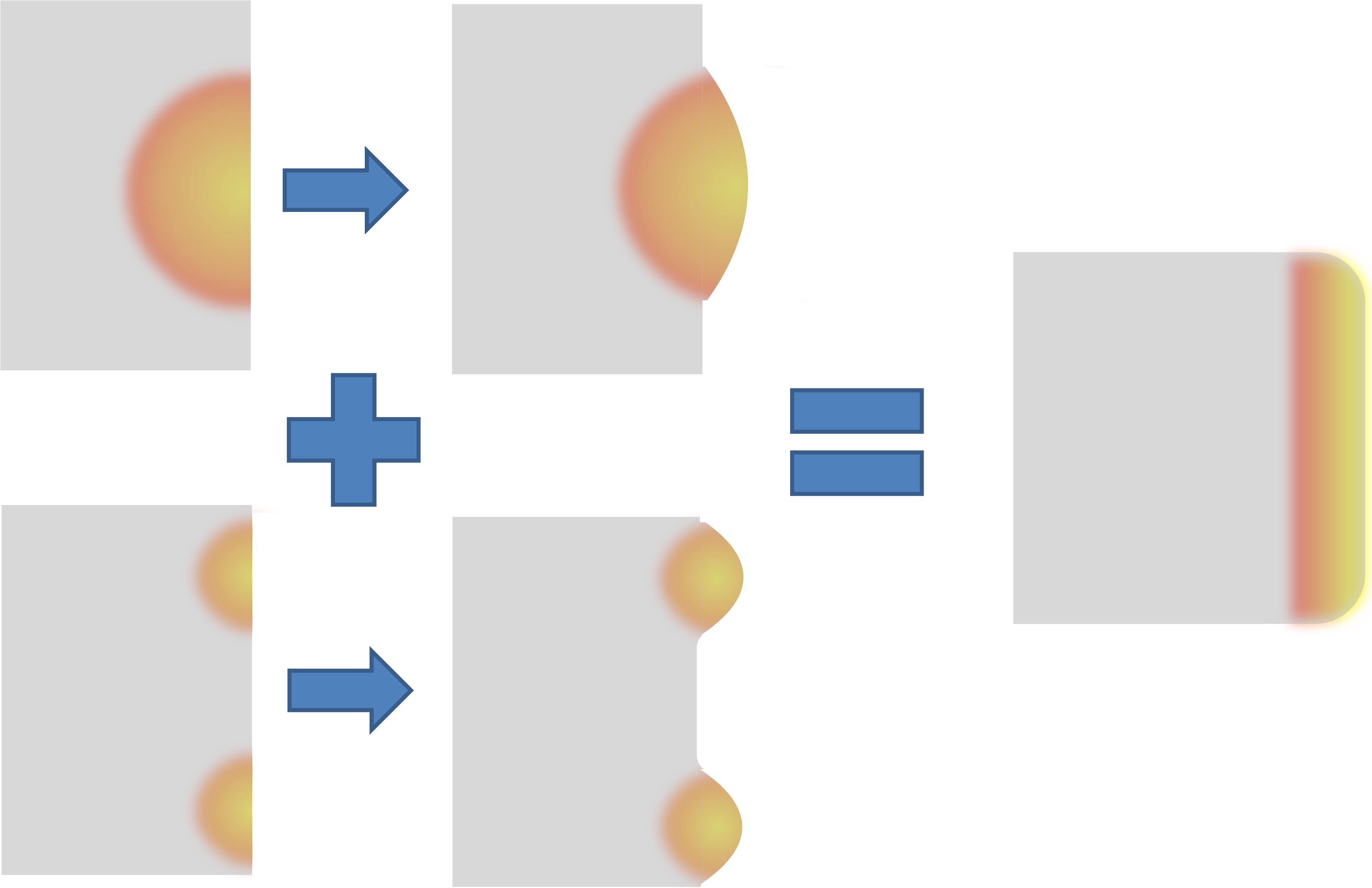
Test Mass (ITM or ETM)

Thermal deformation due to main IFO beam

Thermal deformation due to TCS

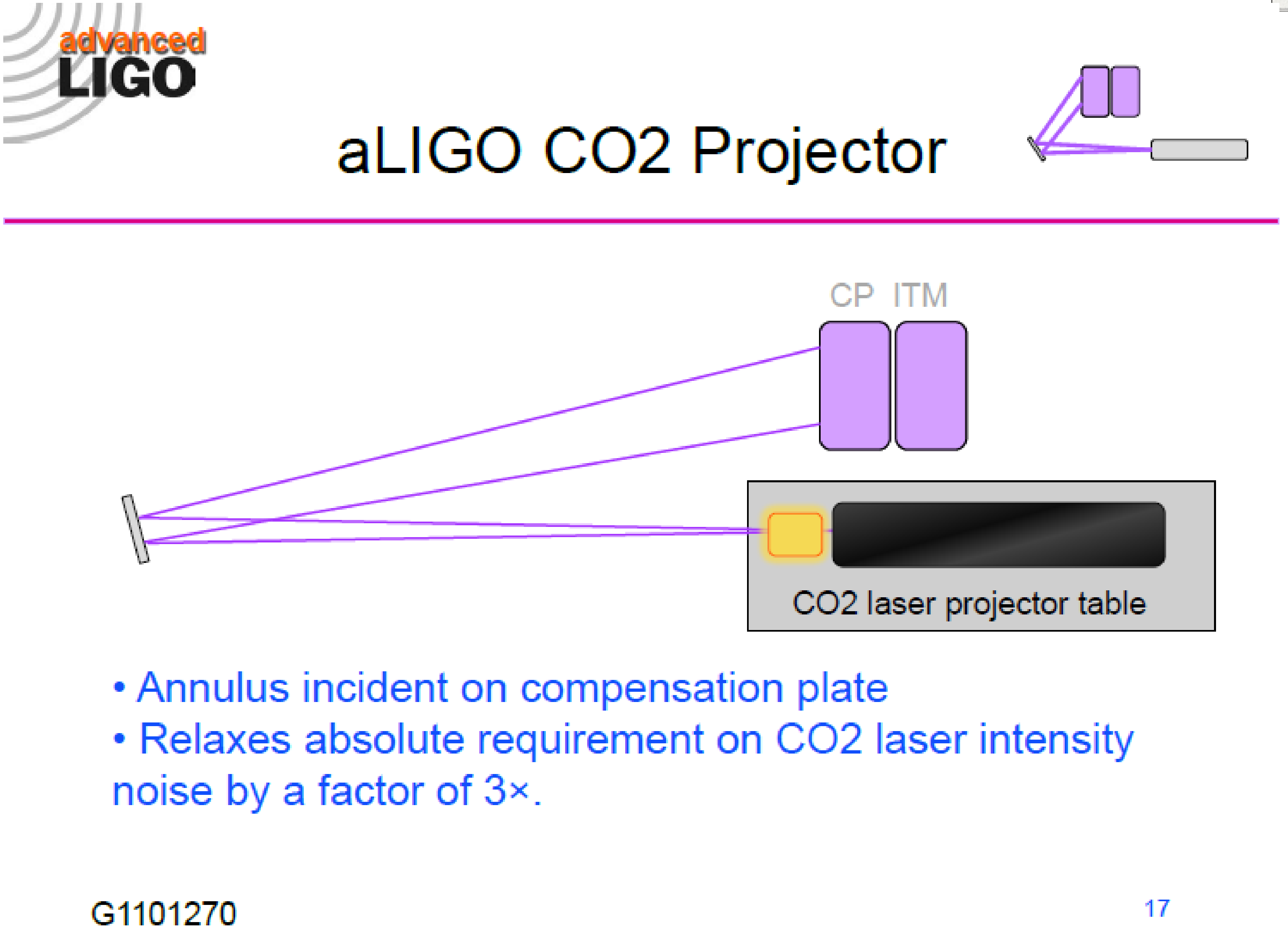
No lens effect, even thermal expansion

Compensate for deformations



Actuator: CO2 Laser

From Aidan Brooks “Advanced LIGO Thermal Compensation System (TCS)” G1101270



aLIGO CO2 Projector

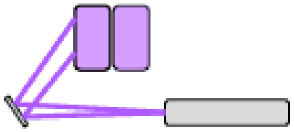
- Annulus incident on compensation plate
- Relaxes absolute requirement on CO2 laser intensity noise by a factor of 3×.

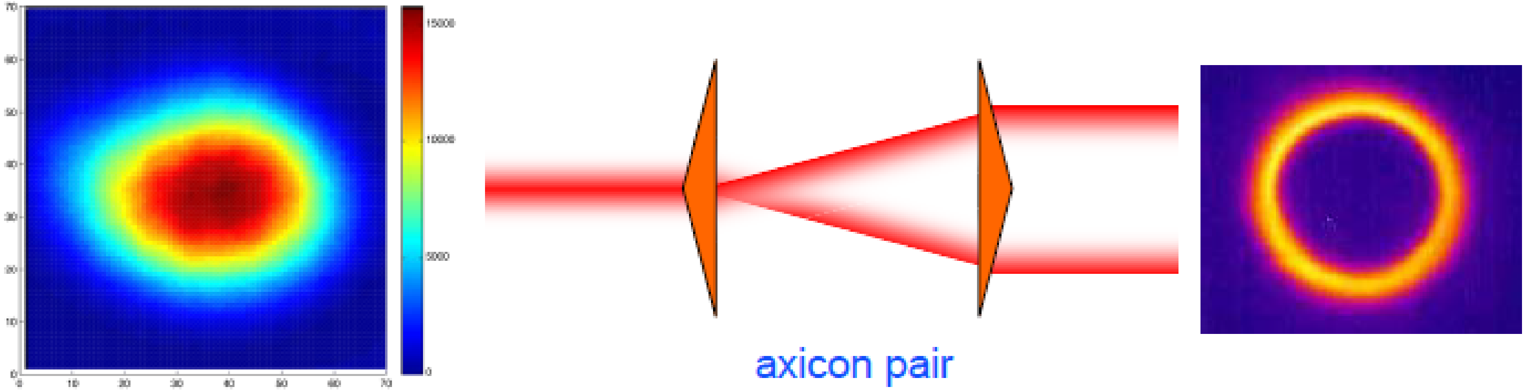
G1101270

17

Actuator: CO2 Laser

Beam profile and beam shaping



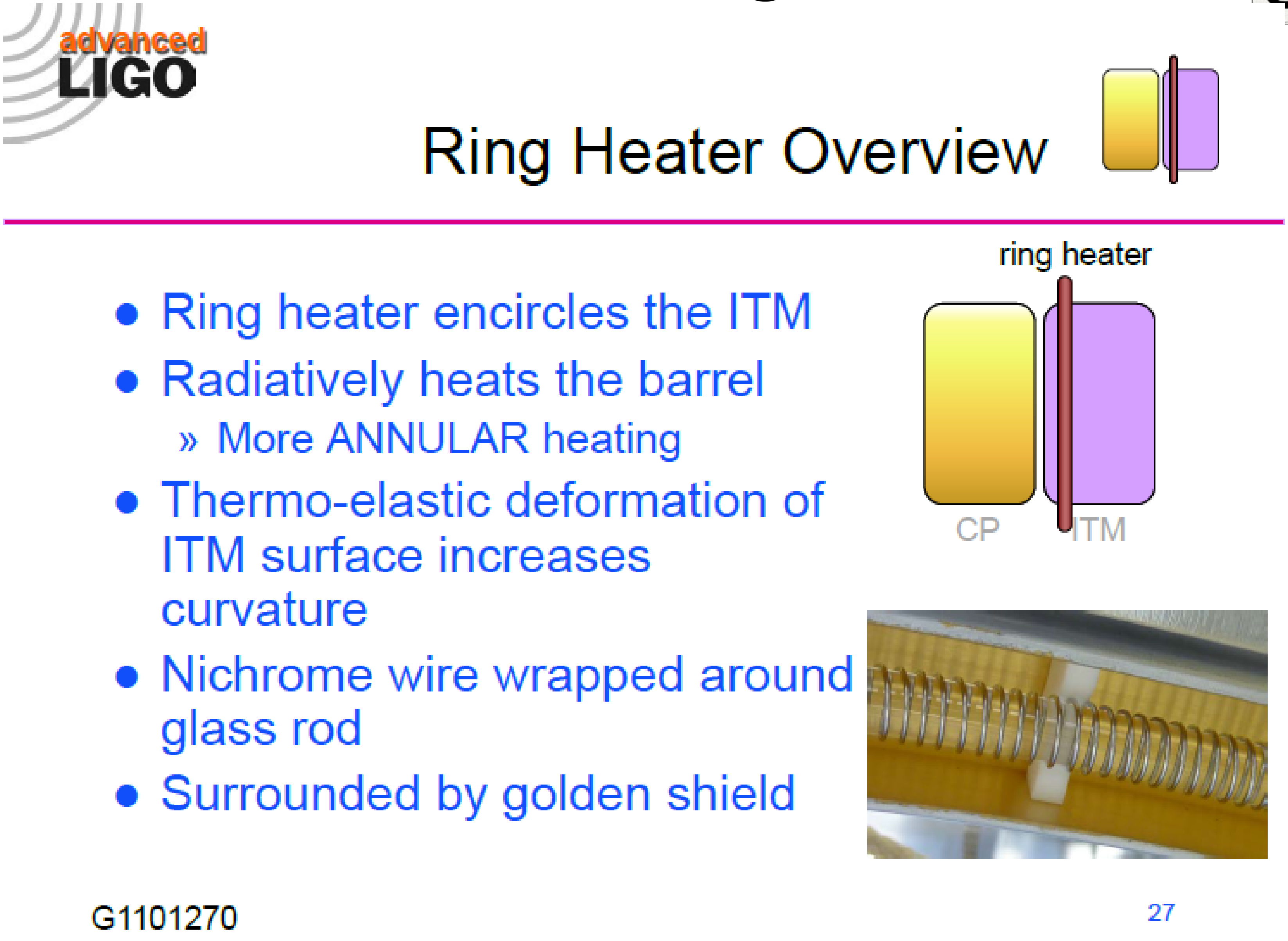


- Initial beam is elliptical
- Will need beam re-shaping
- Axicons will create an annulus

From Aidan Brooks “Advanced LIGO Thermal Compensation System (TCS)” G1101270

Actuator: Ring Heater

From Aidan Brooks “Advanced LIGO Thermal Compensation System (TCS)” G1101270

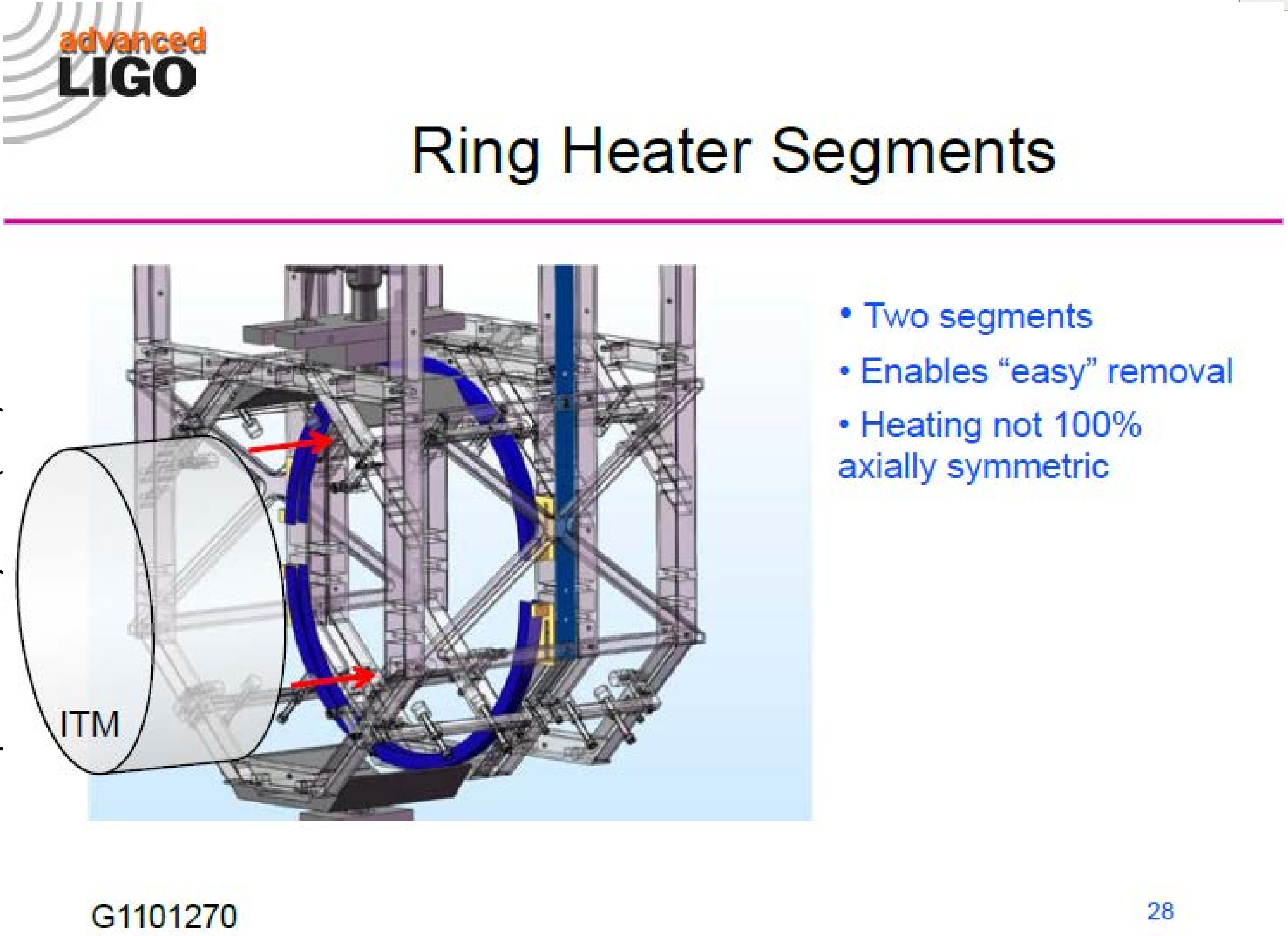


Ring Heater Overview

- Ring heater encircles the ITM
- Radiatively heats the barrel
  - » More ANNULAR heating
- Thermo-elastic deformation of ITM surface increases curvature
- Nichrome wire wrapped around glass rod
- Surrounded by golden shield

Actuator: Ring Heater

From Aidan Brooks “Advanced LIGO Thermal Compensation System (TCS)” G1101270



Ring Heater Segments

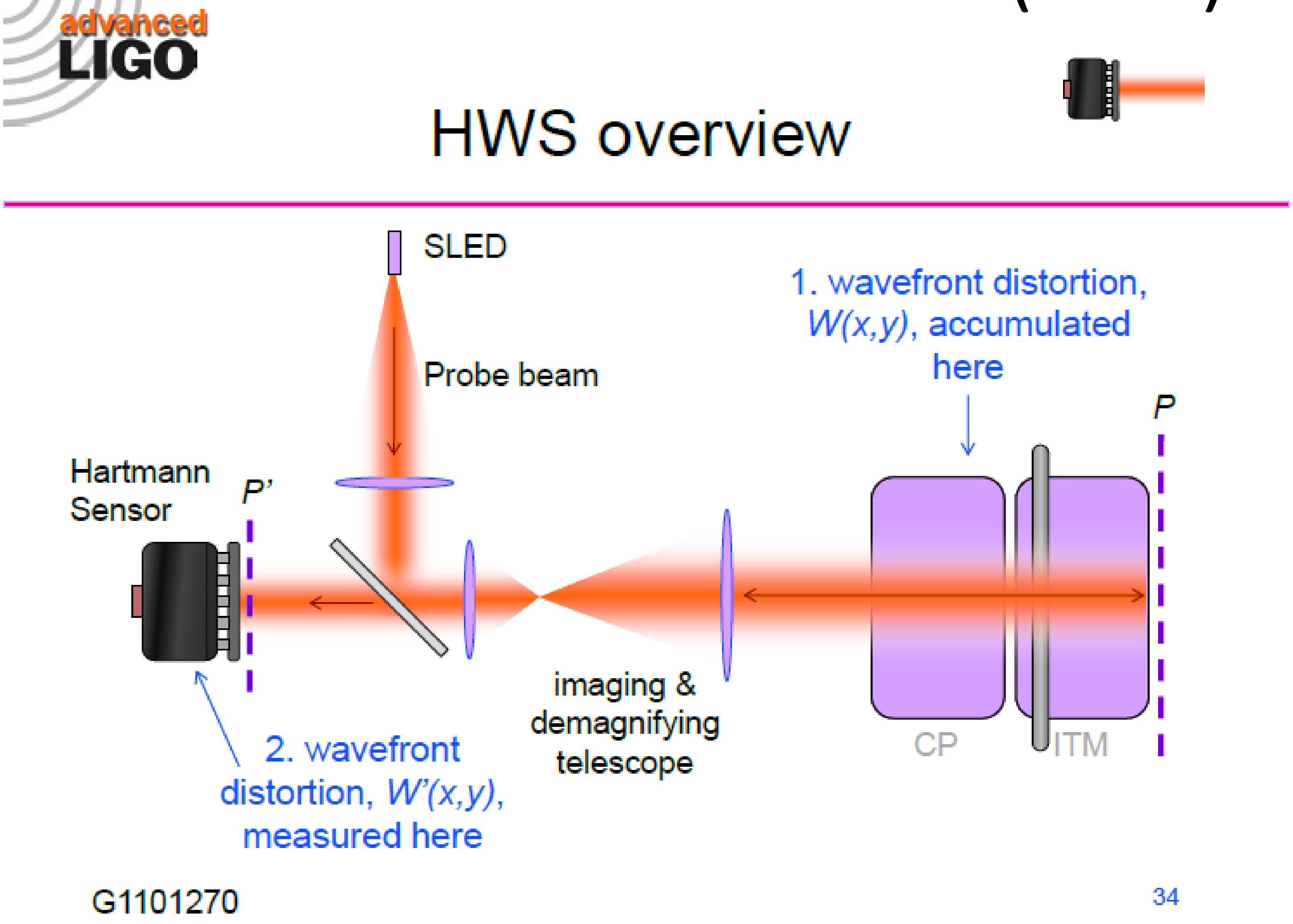
- Two segments
- Enables “easy” removal
- Heating not 100% axially symmetric

G1101270

28

Sensor:
Hartmann Wavefront Sensor (HWS)

From Aidan Brooks “Advanced LIGO Thermal Compensation System (TCS)” G1101270



HWS overview

1. wavefront distortion, *W(x,y)*, accumulated here

2. wavefront distortion, *W’(x,y)*, measured here

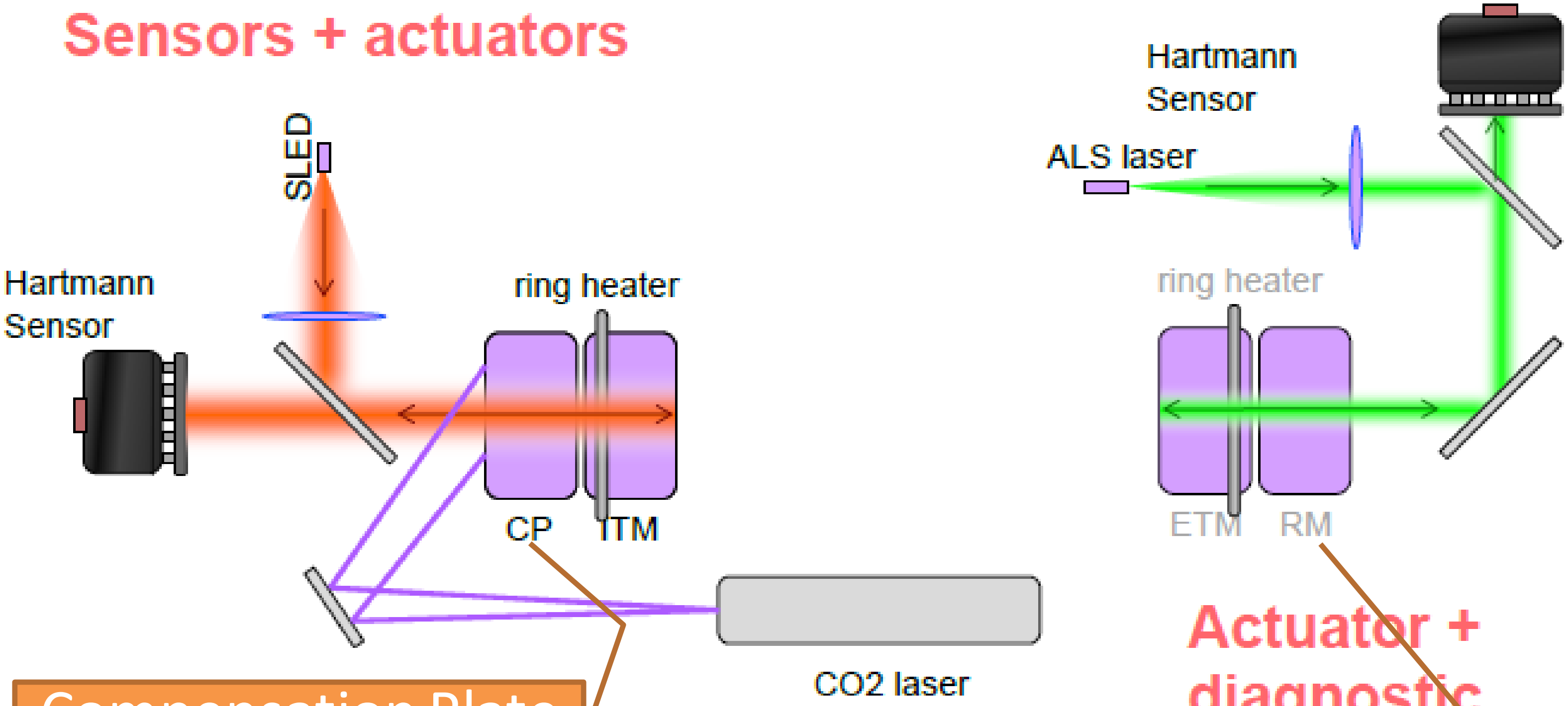
G1101270

34

aLIGO TCS Overview

From Aidan Brooks "Advanced LIGO Thermal Compensation System (TCS)" G1101270

Sensors + actuators



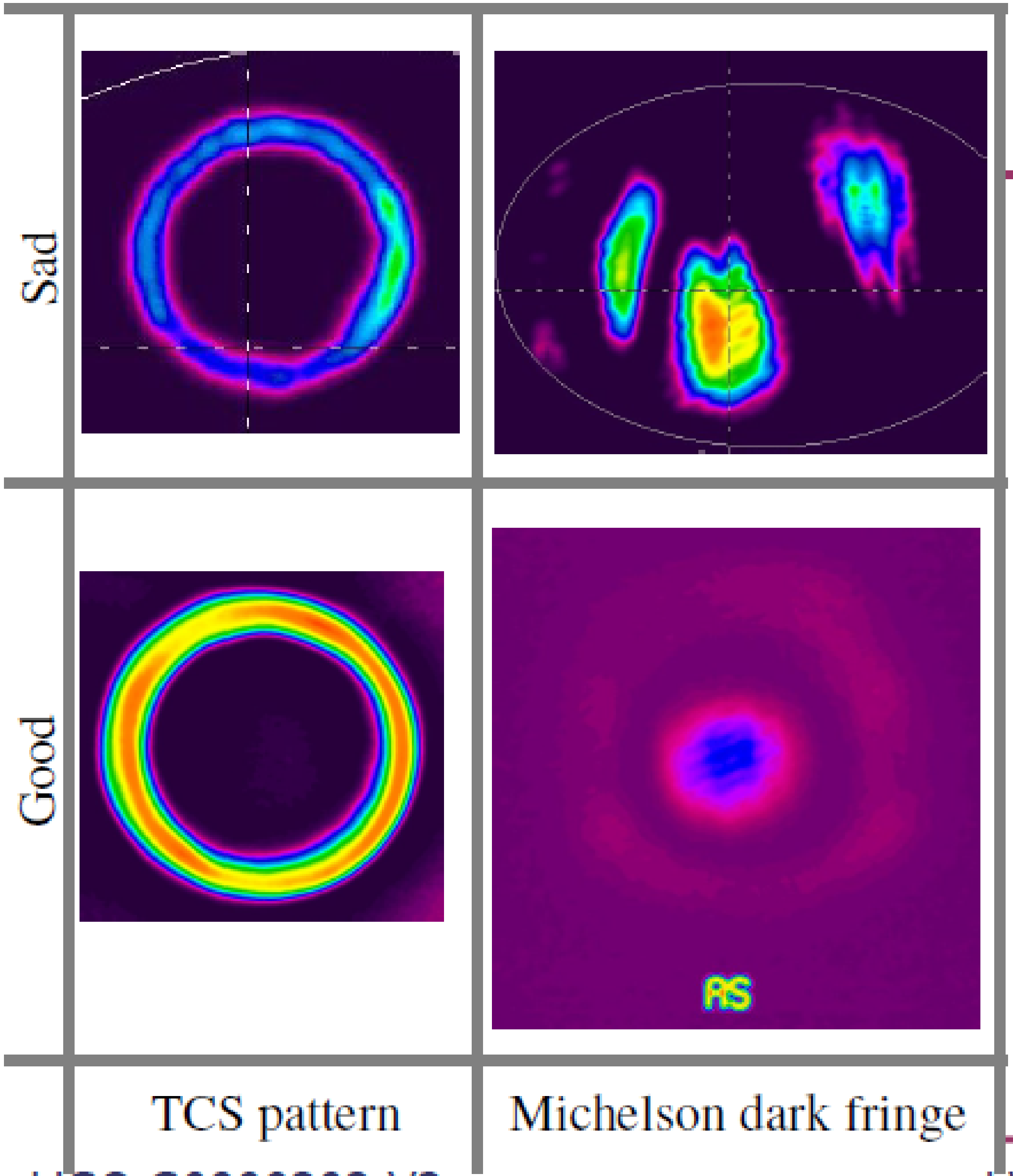
Actuator + diagnostic

Compensation Plate (CP) or Reaction Mass (RM)

Reaction Mass (RM)

15

TCS: Heating pattern



- Took months to have "good" pattern
  - But we're there!
- "good" and "not so good" makes or breaks high power
- Now we can (finally!) focus on "how much heat" optimization

From Keita Kawabe "Enhanced LIGO Commissioning" G0900202

Summary

- Automatic Alignment and Wavefront sensors
  - The amount of first-order TEMs (01 or 10) provides alignment information
- Input Mode Cleaner
  - Suspended triangular cavity
  - Spatially filters incoming laser beam (non-TEM00 modes rejected)
  - Provides additional frequency noise and beam jitter suppression
- Output Mode Cleaner
  - Four-mirror bow tie configuration
  - Sidebands are rejected along with non-TEM00 modes
- Thermal Compensation System (TCS)
  - Compensates for thermal induced deformations ($\sim 800\ kW$ stored in arms)
  - Optimizes IFO coupling to TEM00 (light that carries GW information)

Group Activity

- Post questions on the board
- Group discussion
- In preparation for tomorrow
  - Read “The Advanced LIGO Length Sensing and Control Final Design” T1000298-T