



Adaptive Mode Matching for the Output Mode Cleaner in LIGO

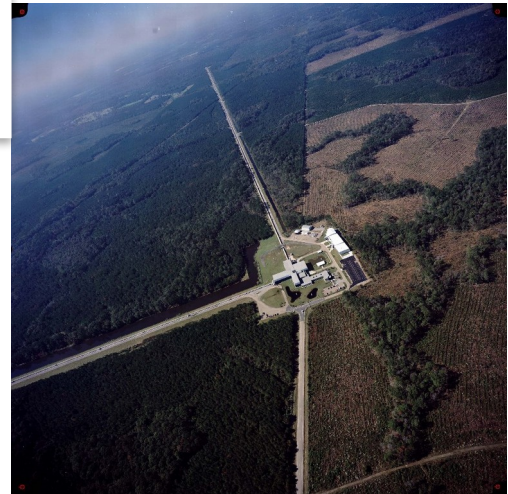
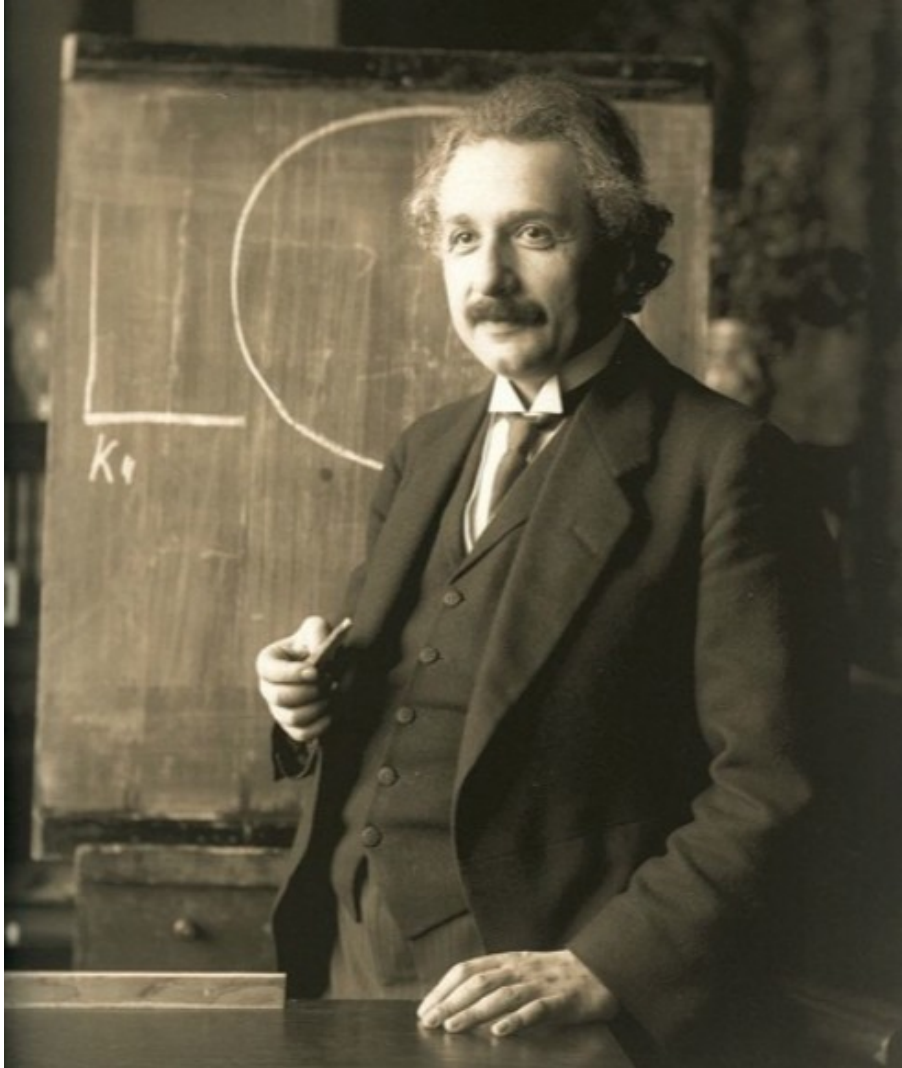
Fabian Magaña-Sandoval

on behalf of the LIGO Scientific Collaboration

PI Professor Stefan Ballmer

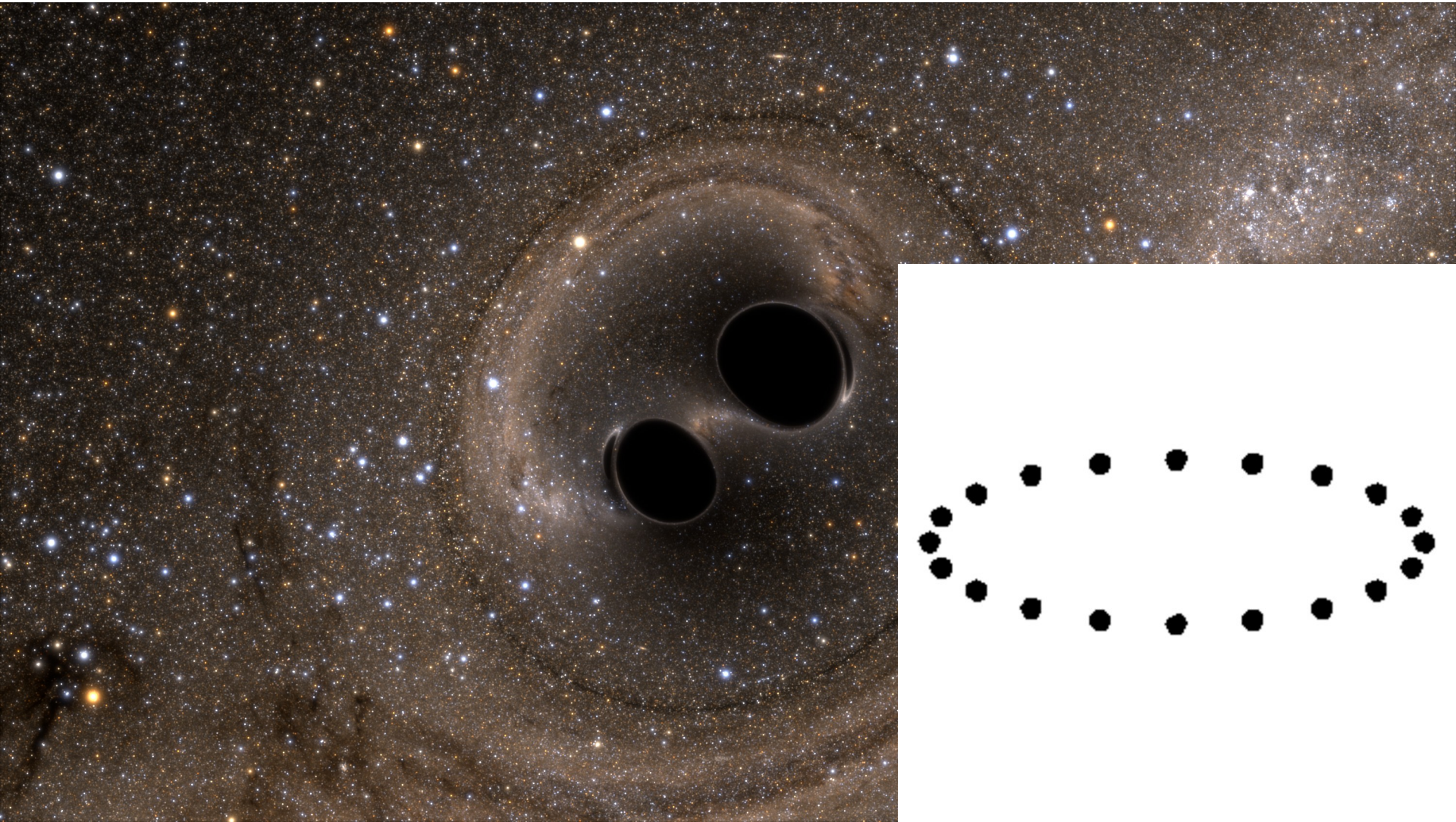
Paul Fulda, Antonio Perreca, Jax Sanders,
Thomas Vo, Daniel Vander-Hyde, Erik Muniz

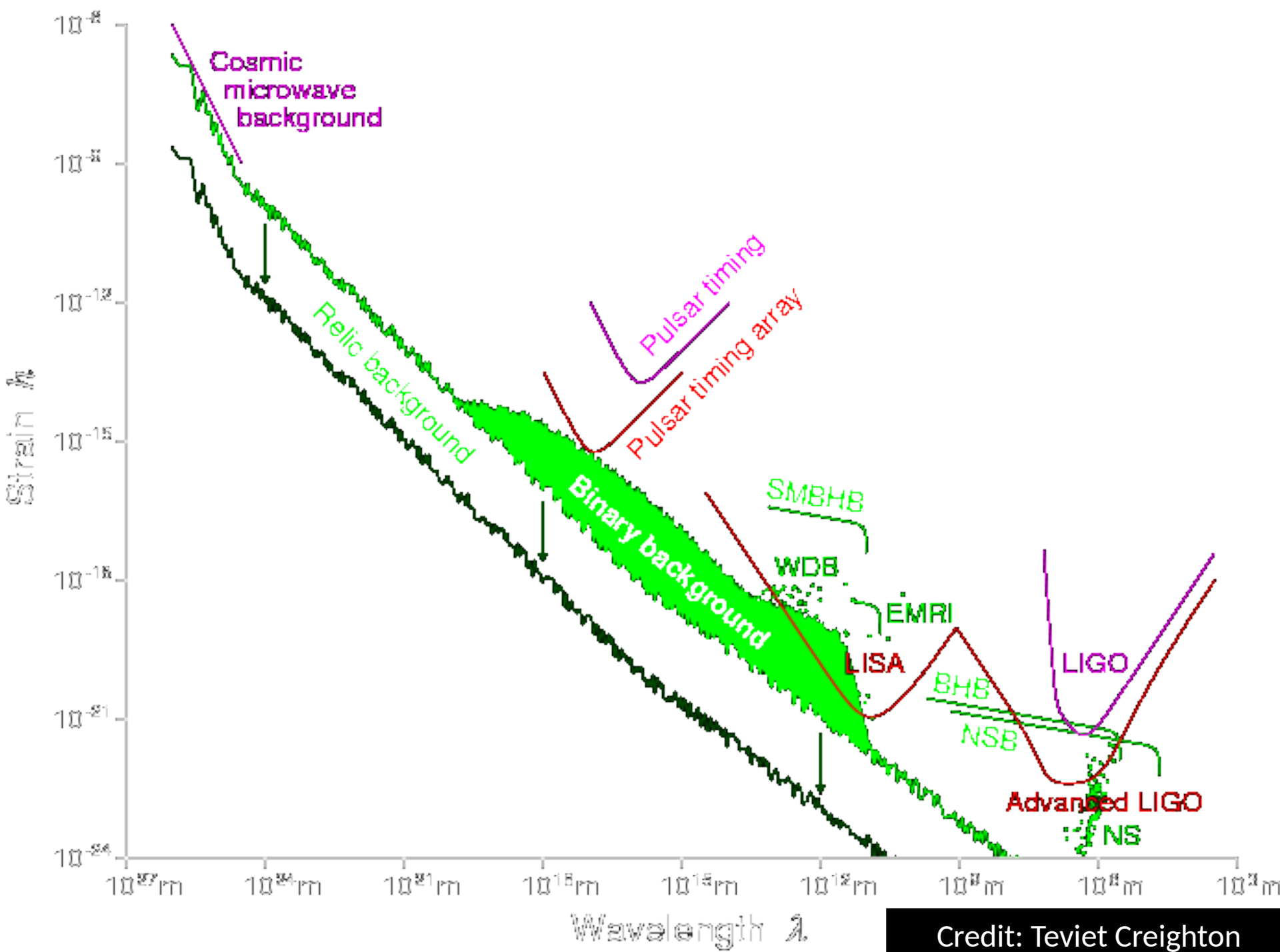
Era of Gravitational Wave Astronomy



Gravitational Waves

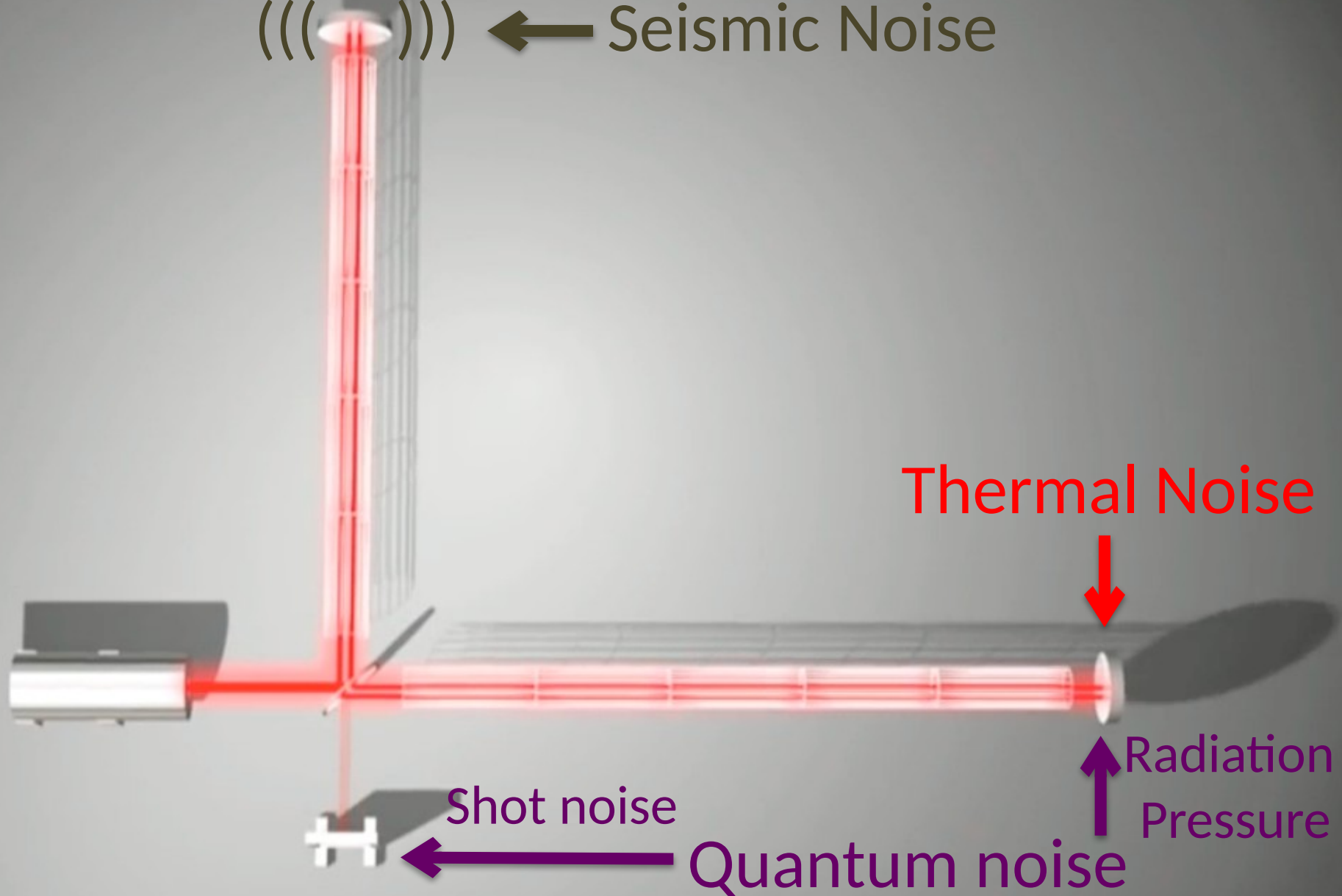
Perturbations in space-time



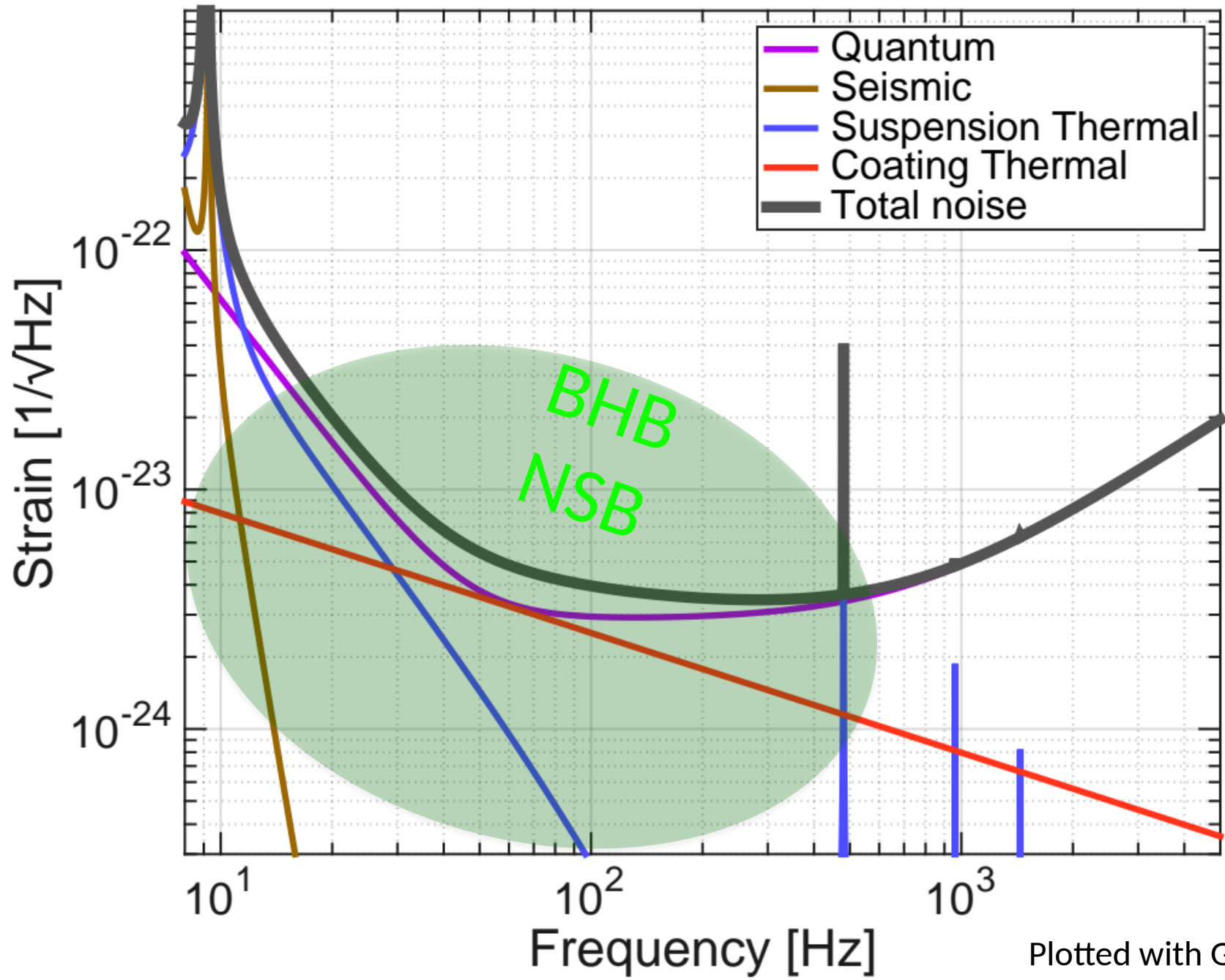


LIGO Noise

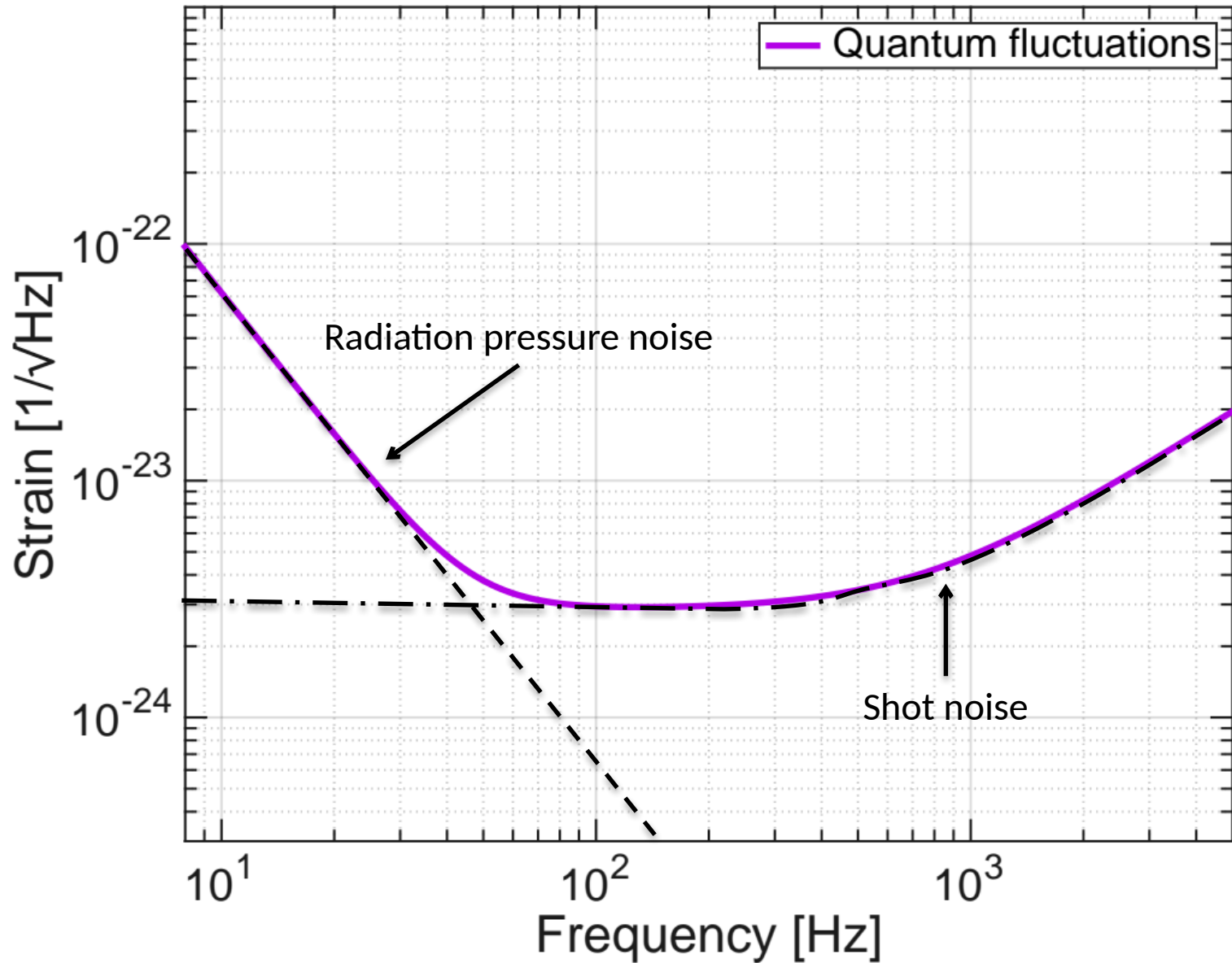
((())) ← Seismic Noise



Advanced LIGO Noise



Quantum noise



Quantum noise

However, we can trick nature...

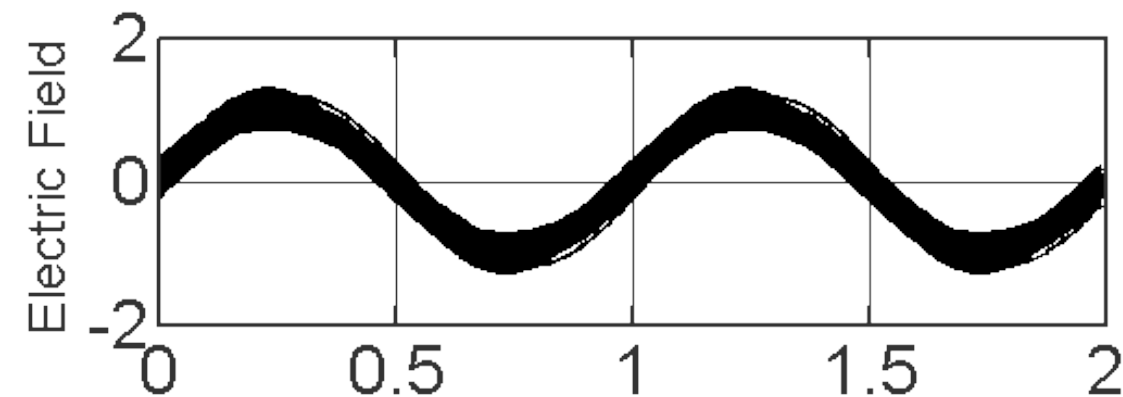
$$\Delta x \Delta p \geq \frac{\hbar}{2} \longrightarrow \Delta A, \Delta \phi$$

Strain is only sensitive to phase!

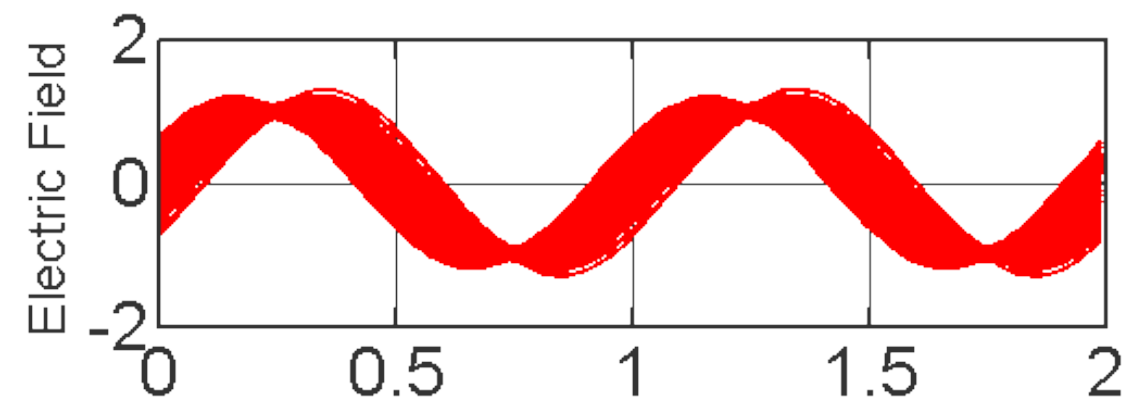
Dump all uncertainty into amplitude

This is called squeezing

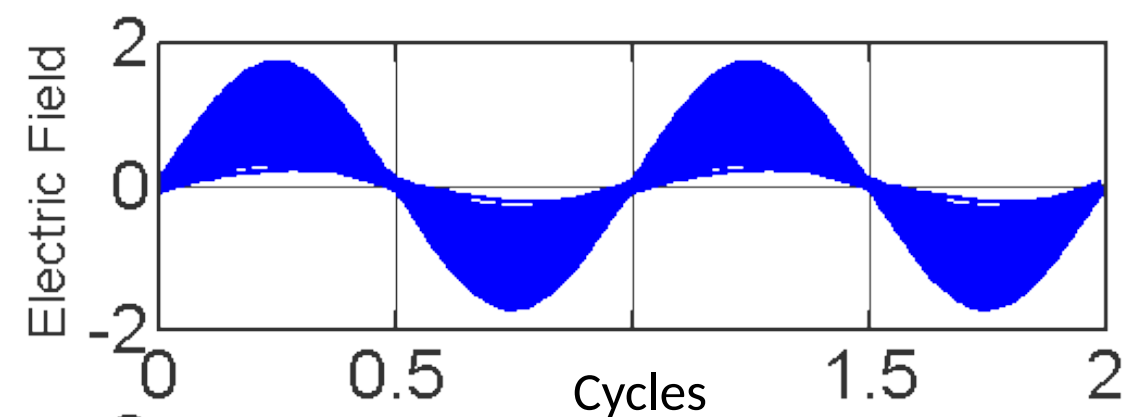
Squeezing



No squeezing

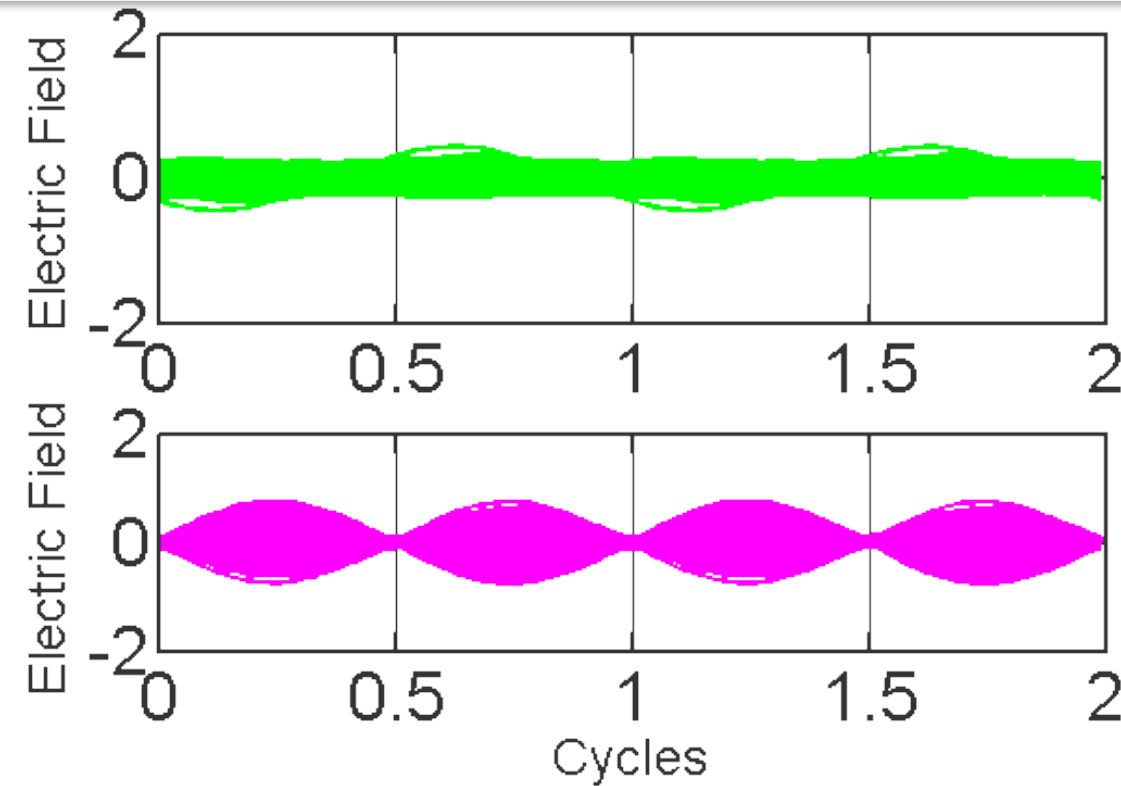


Amplitude squeezed



Phase squeezed

Squeezed vacuum



Vacuum fluctuations

Squeezed vacuum

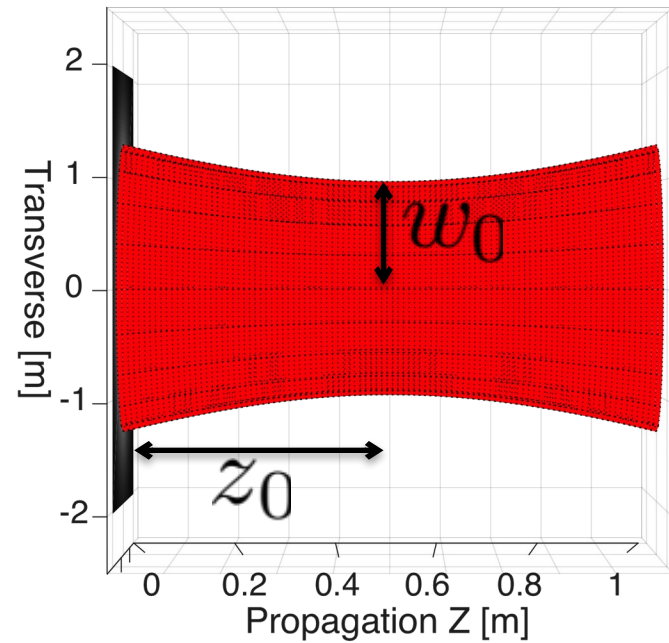
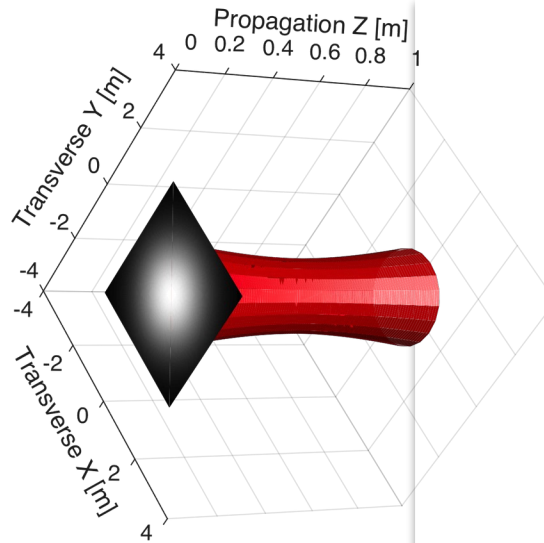
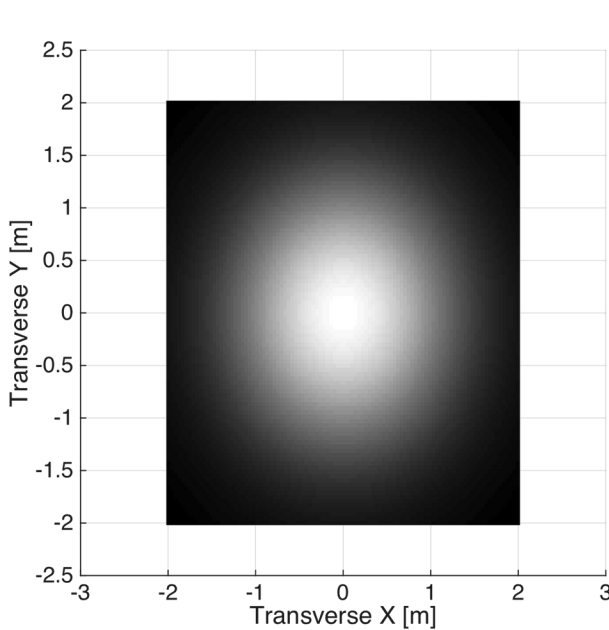
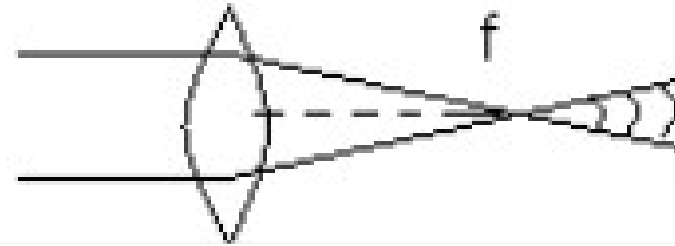
Before we continue...

Gaussian beams

Fabry-Pérot cavities

Mode matching

Gaussian beam



Waist size w_0

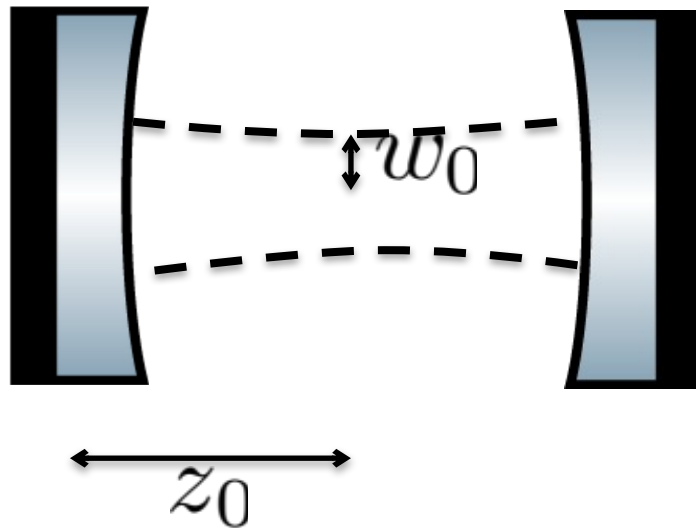
Waist location z_0



$$q(z) = z + i \frac{\pi w_0^2}{\lambda}$$

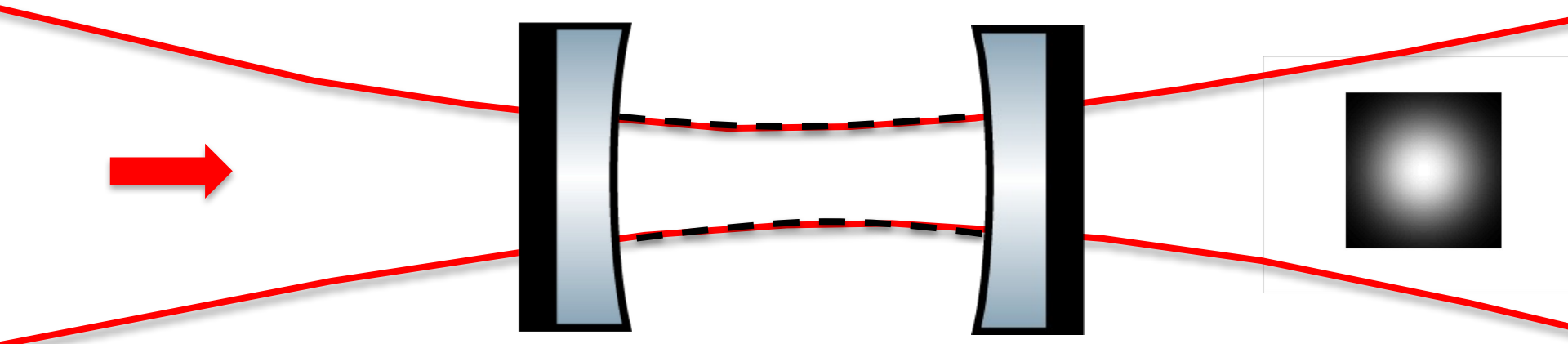
Fabry-Pérot cavity

$$q(z) = z + i \frac{\pi w_0^2}{\lambda}$$



Mode matching

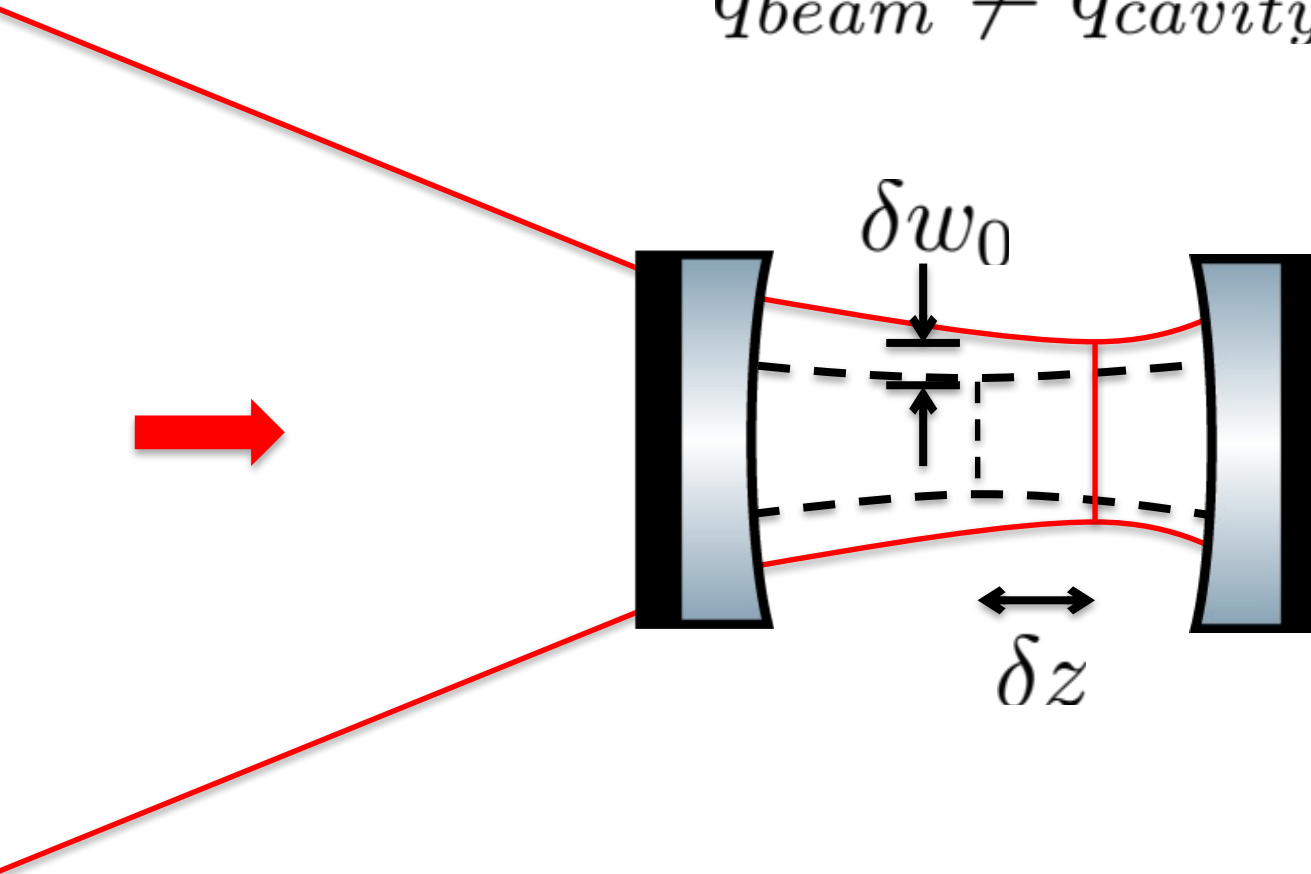
$$q_{beam} \overset{\checkmark}{=} q_{cavity}$$



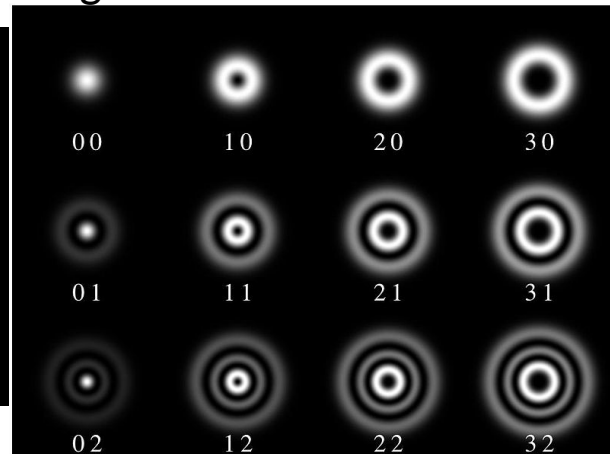
Mode mismatch

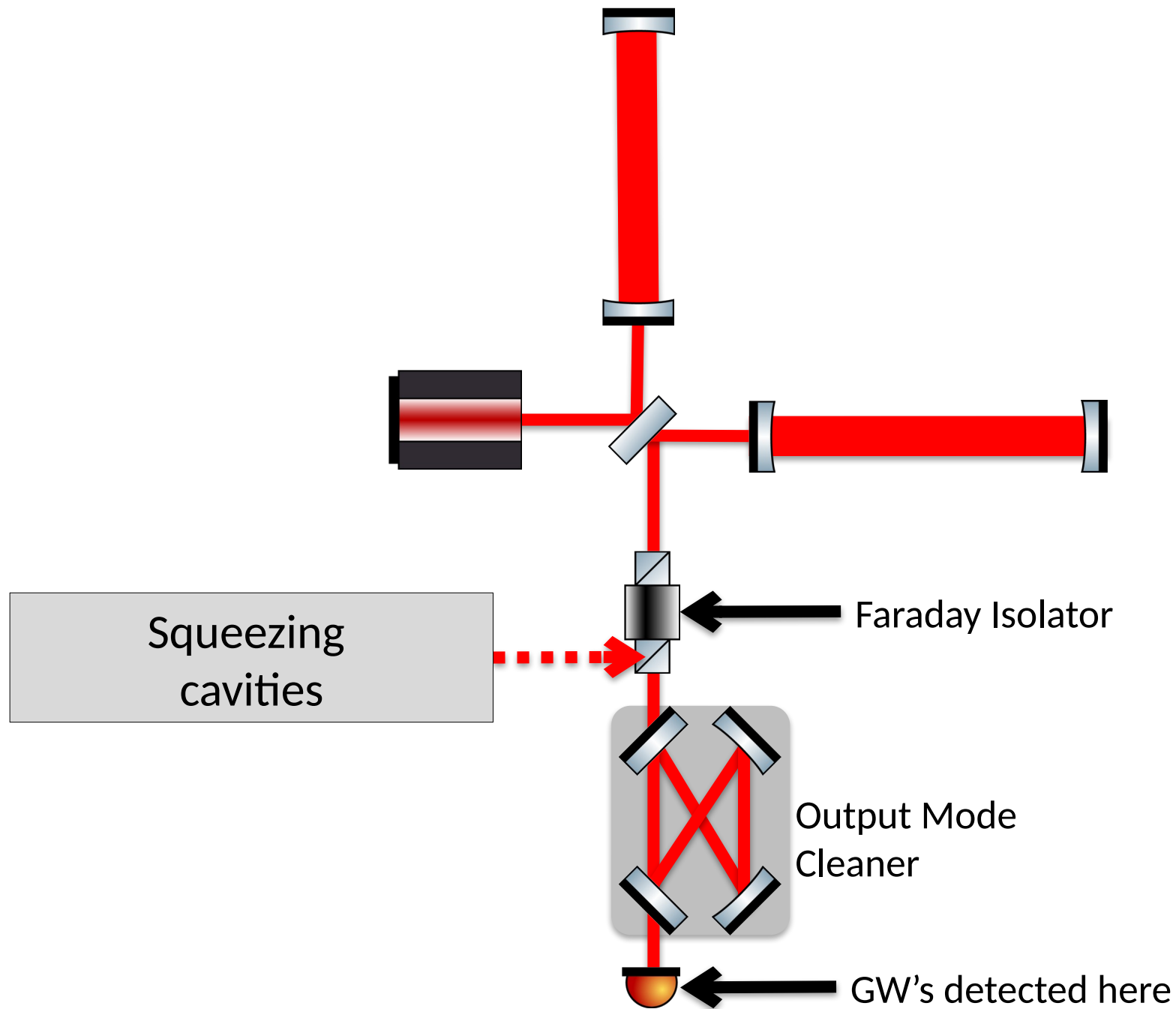


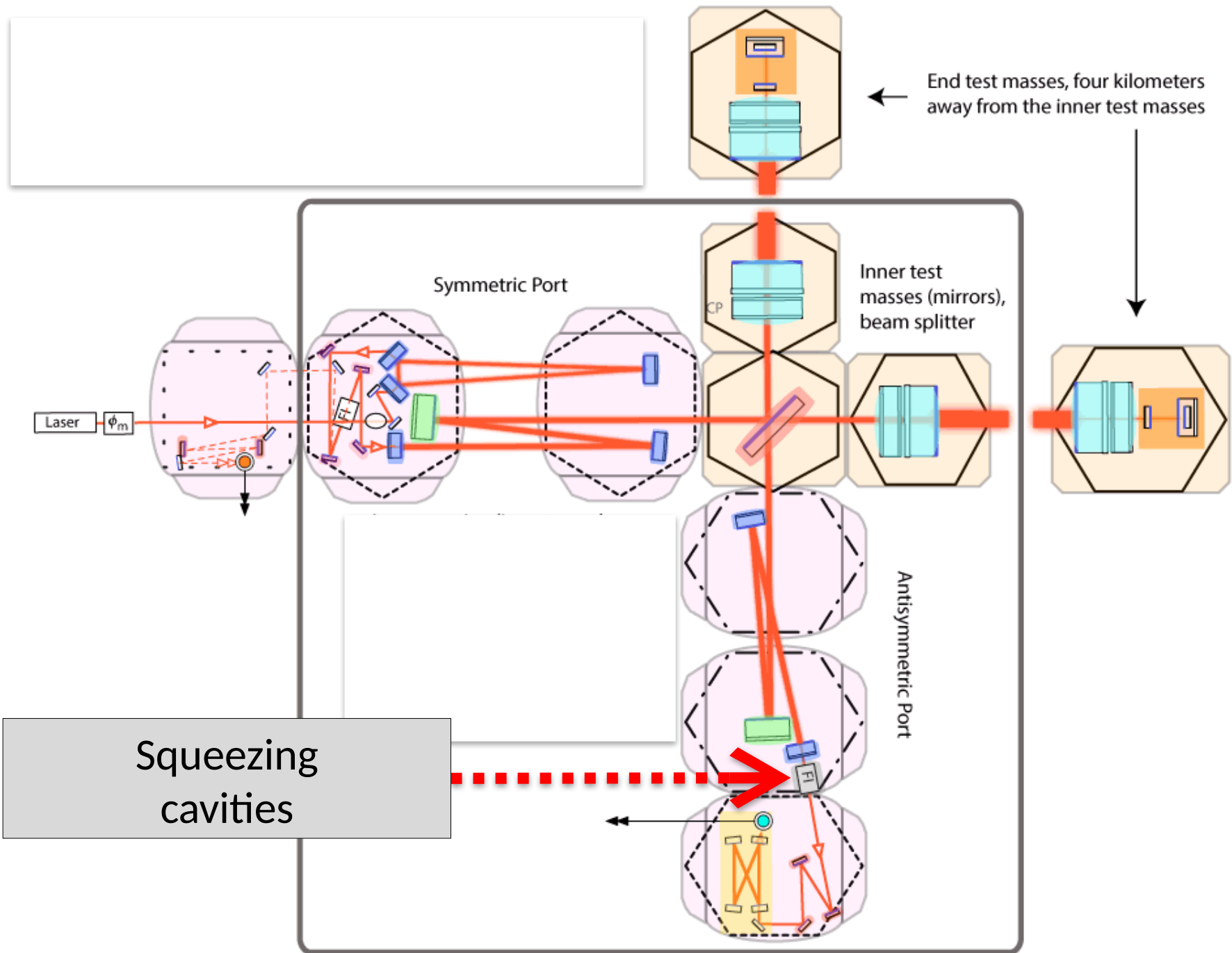
$$q_{\text{beam}} \neq q_{\text{cavity}}$$

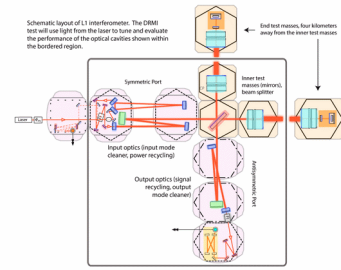


Laguerre-Gaussian modes





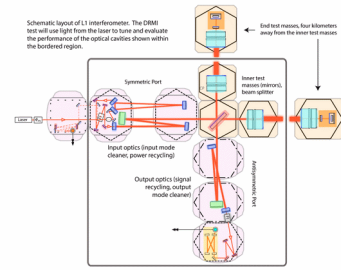




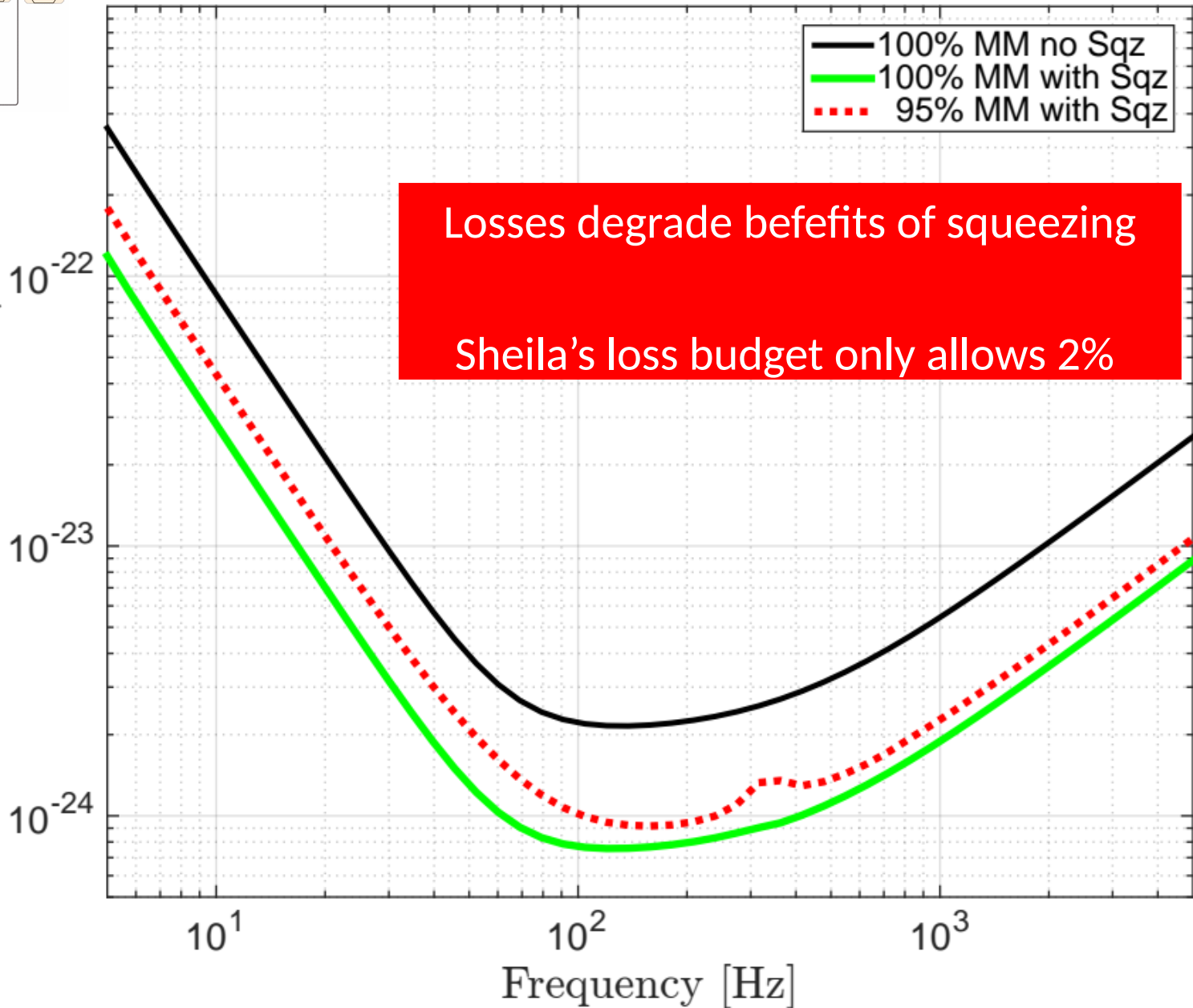
FINESSE modeling

- Advanced LIGO model
- Best Squeezing with 100% mode matching
- Best Squeezing with 95% mode matching

FINESSE model

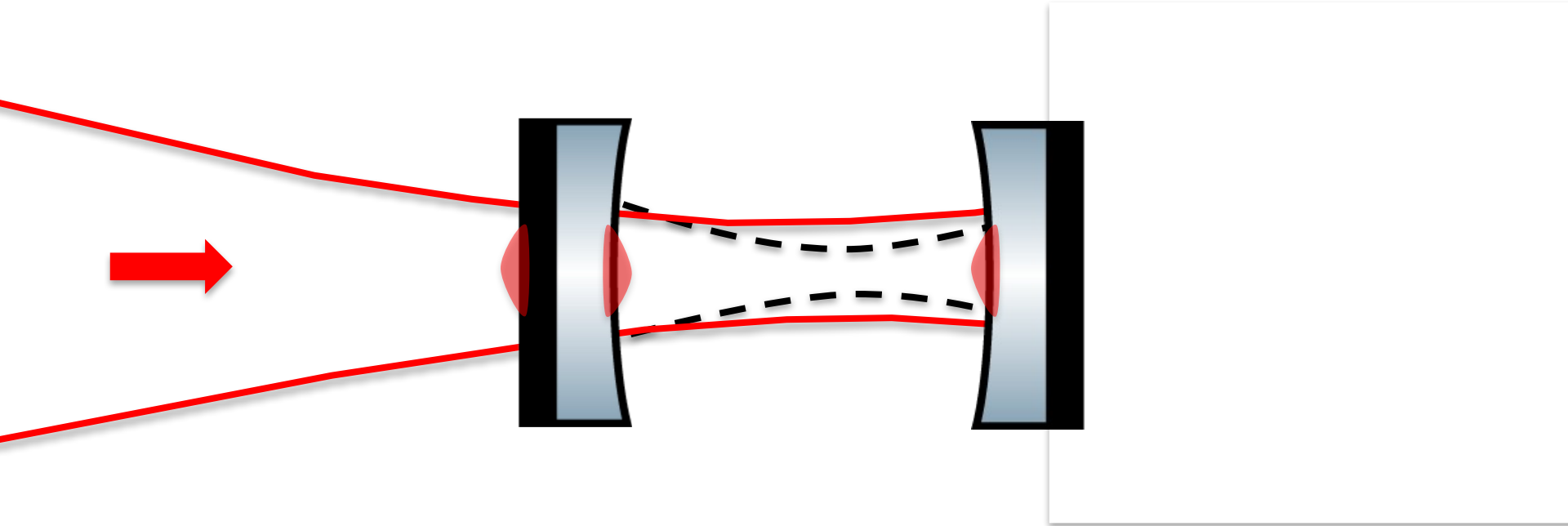


Strain Sensitivity $\frac{1}{\sqrt{Hz}}$



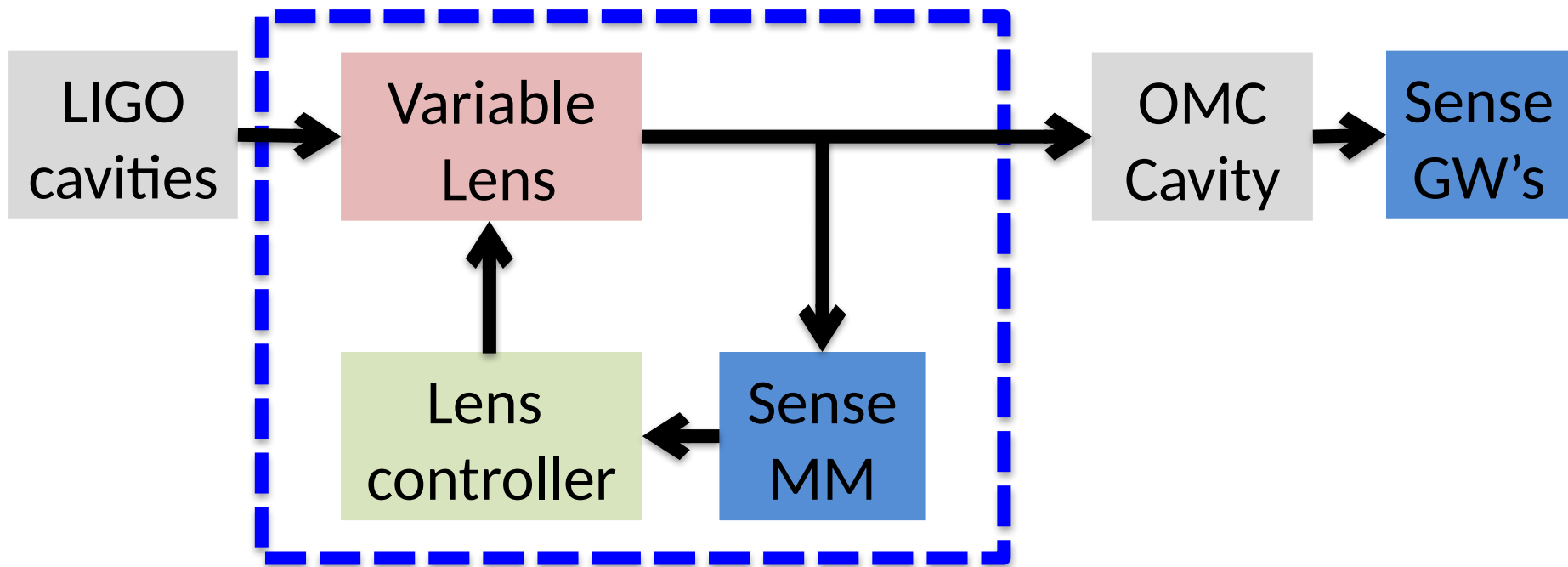
Lets just mode match well once?

We have a dynamic problem

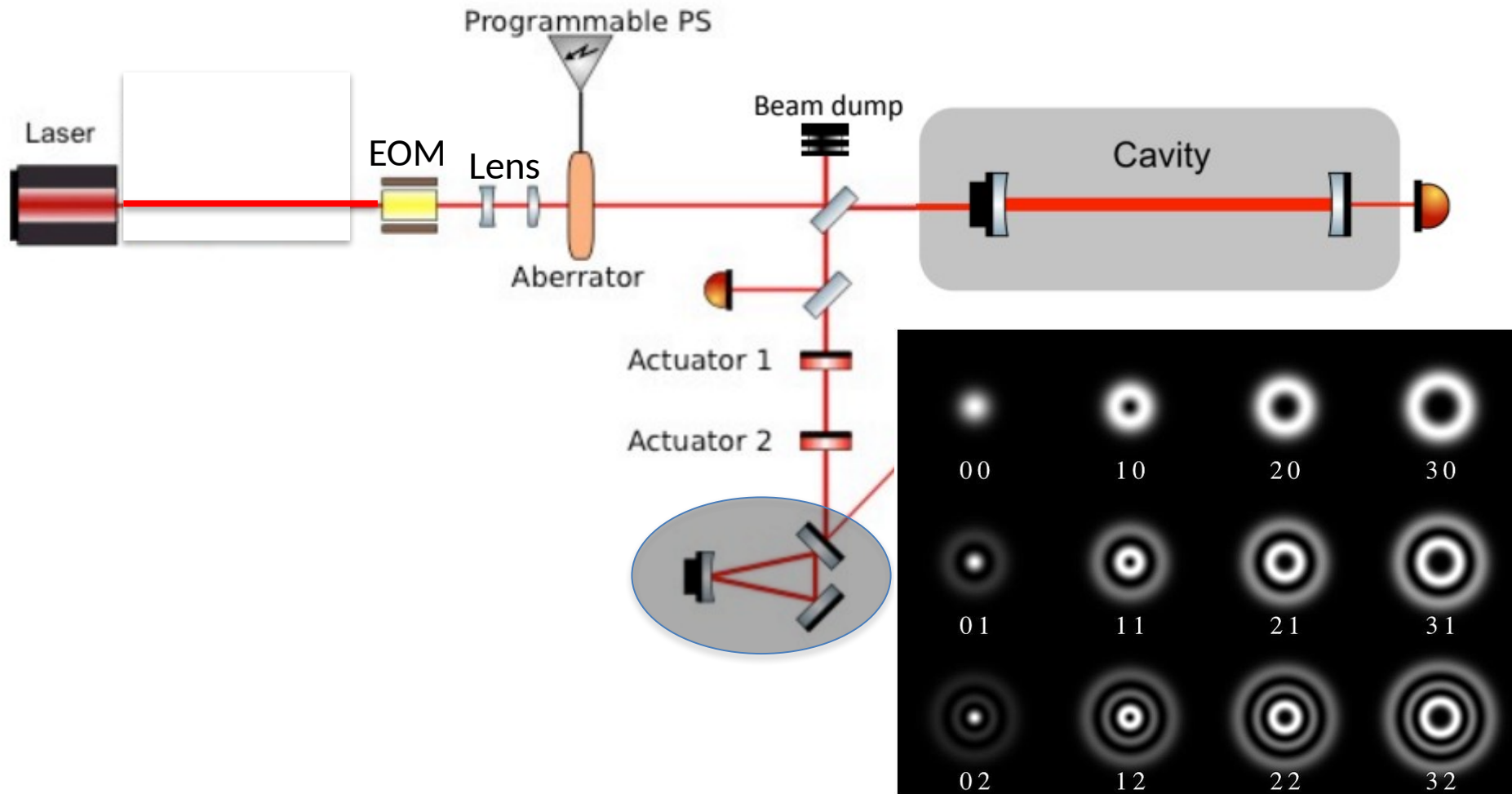


LIGO's Thermal Compensation System brings mode matching to 15% ... we need better than 2%

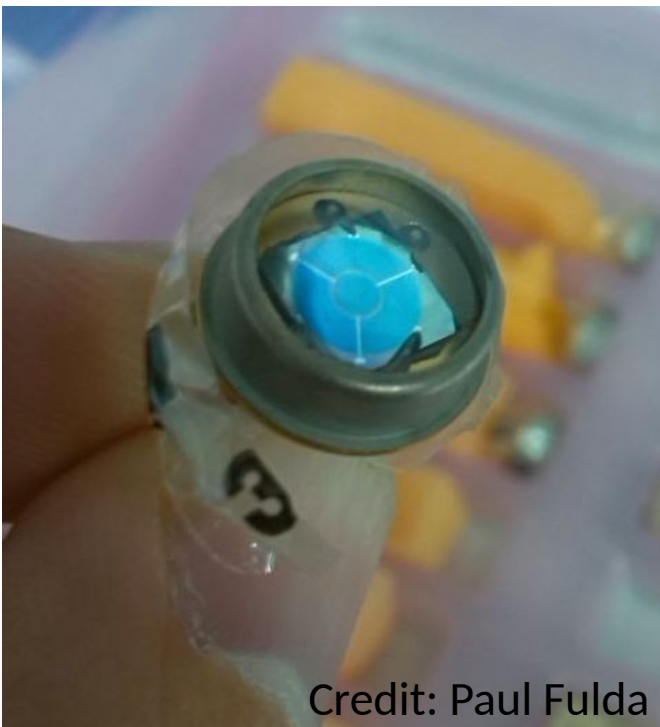
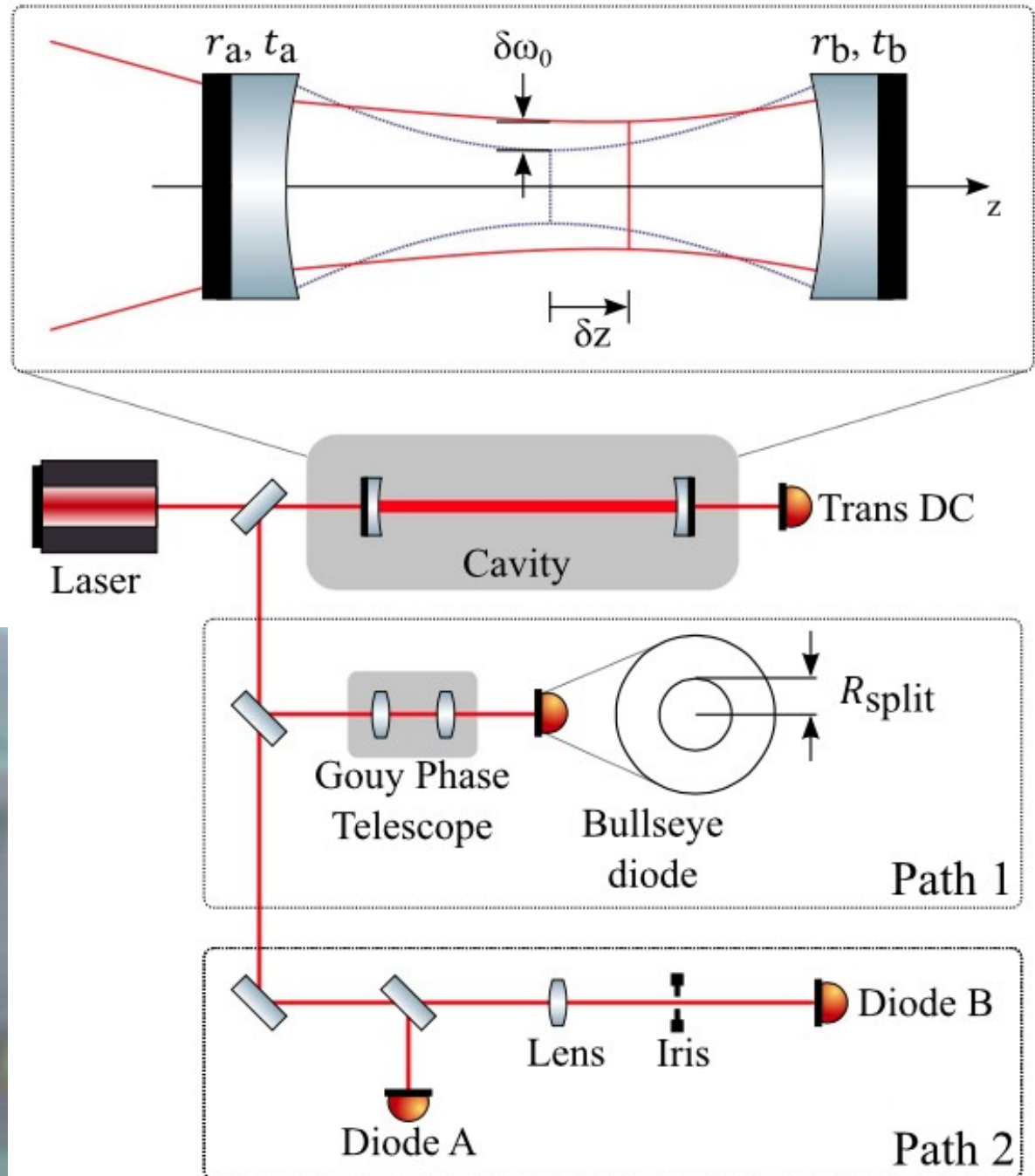
Thus we need Adaptive Mode Matching



Experiment design at SU



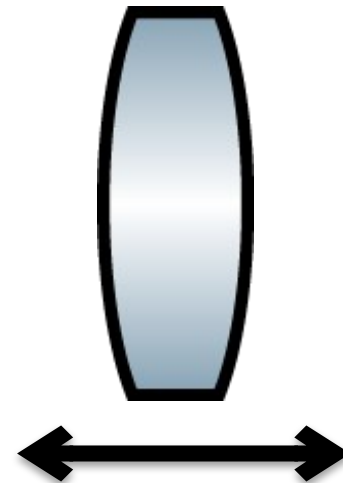
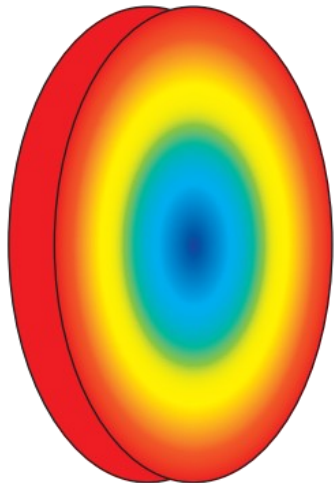
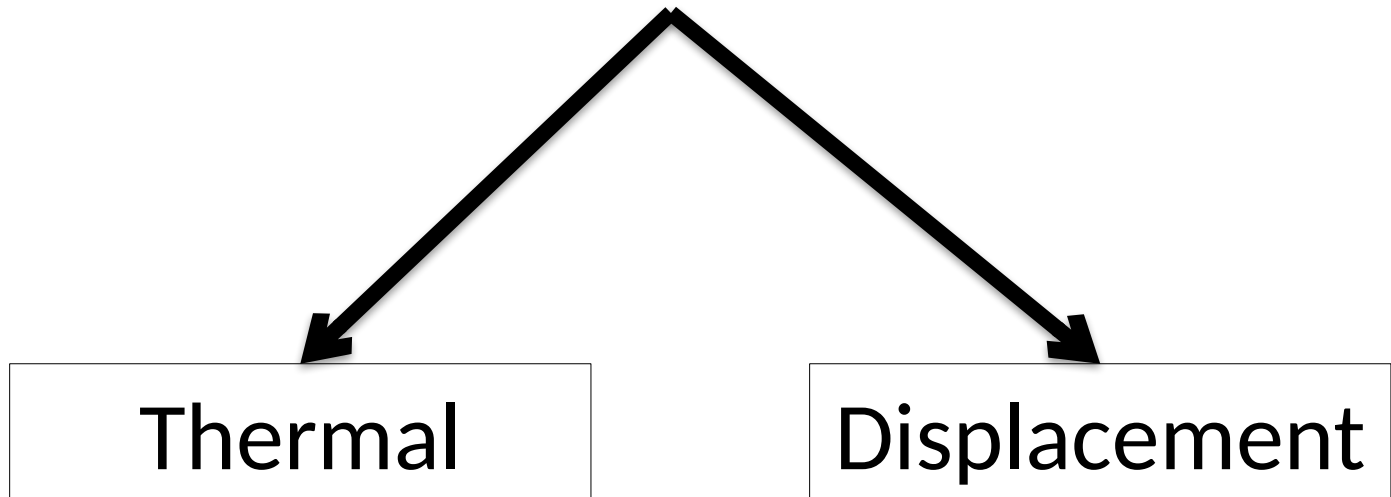
Sensing mode mismatch



Credit: Paul Fulda

Credit: John Miller and Matthew Evans

Actuators



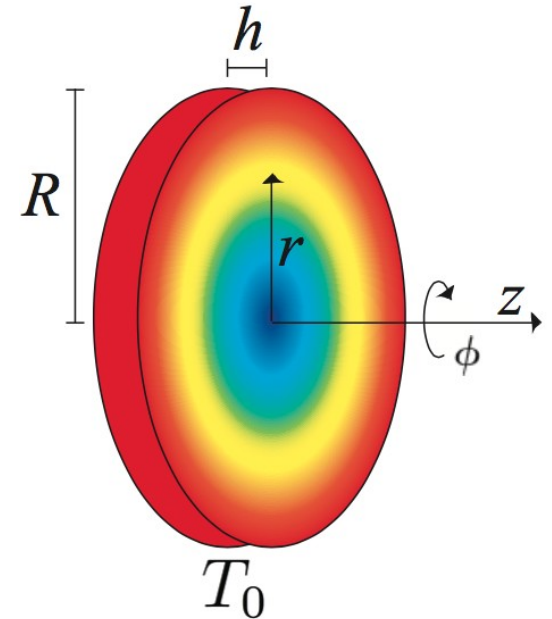
How thermal lensing works

1. Heat diffusion equation

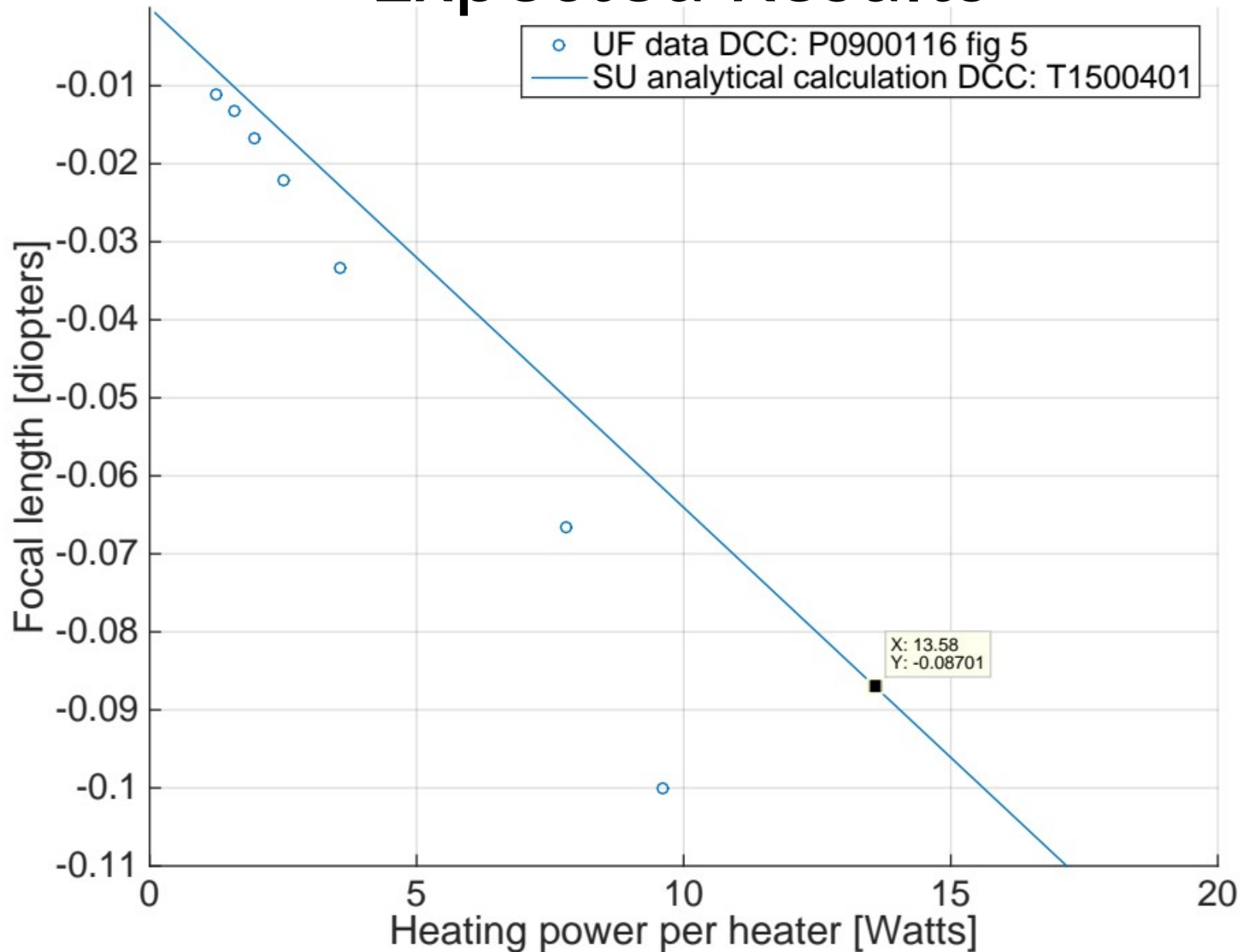
2. Use cylindrical symmetry
Boundary conditions

4. Solve for Temperature profile

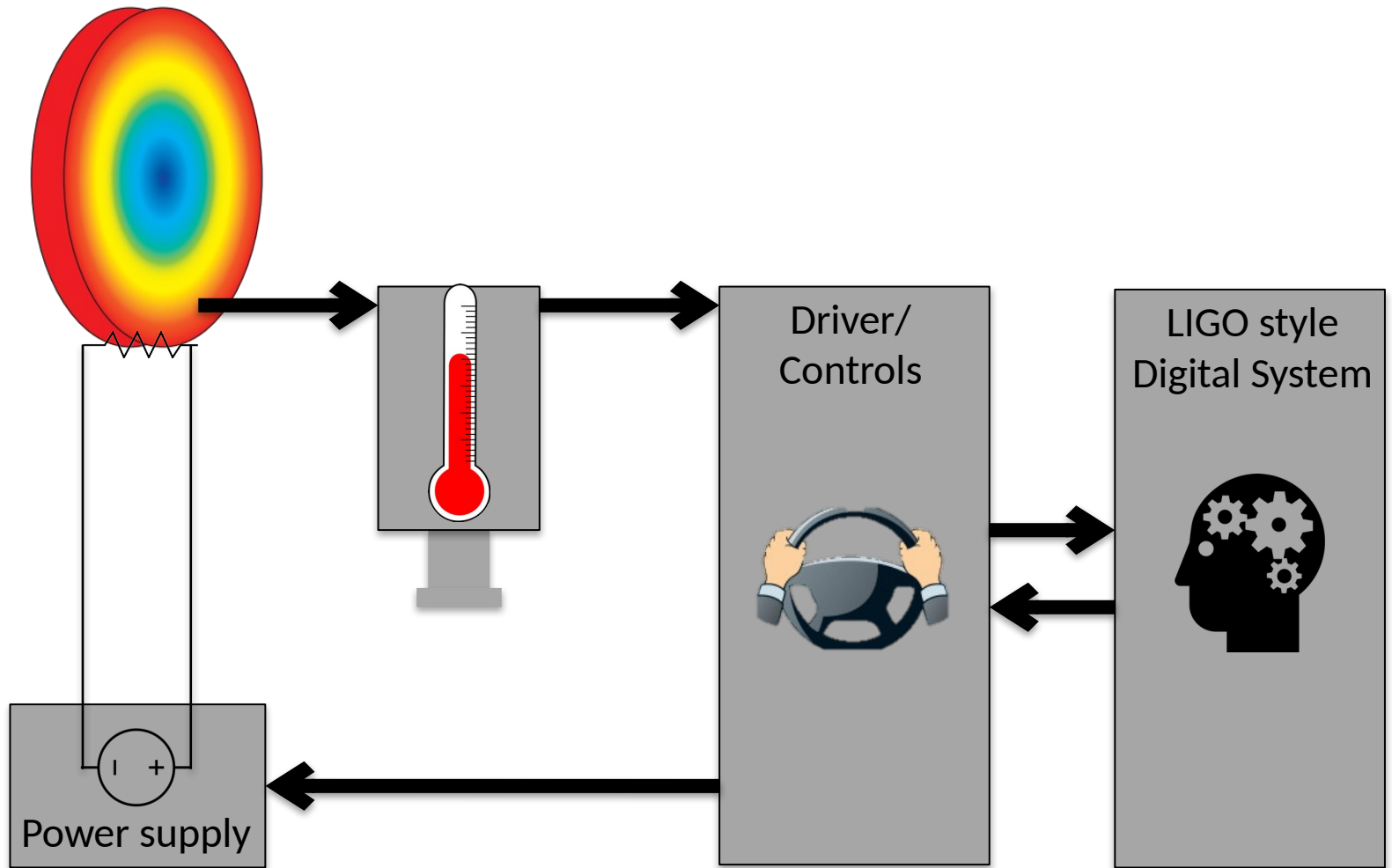
5. Use temperature profile with thermal expansion
Lens curvature profile



Expected Results



Lens hardware



UF design SU modified

Variable lens top bar

VIEW FROM FRONT

VIEW FROM LEFT

VIEW FROM RIGHT

Variable

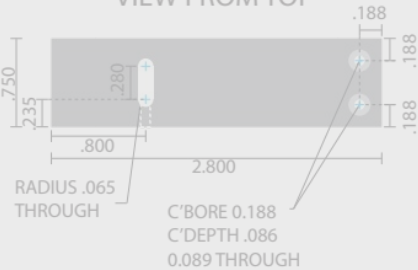
VIEW FROM FRONT



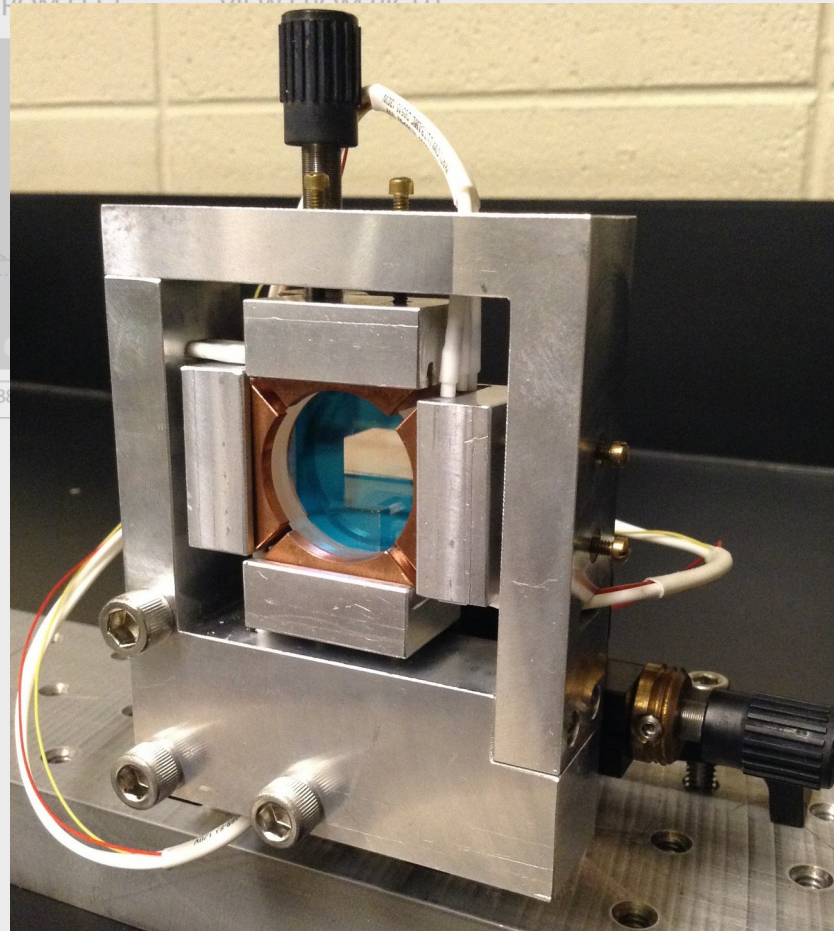
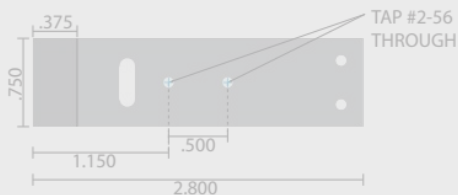
VIEW FROM BACK



VIEW FROM TOP



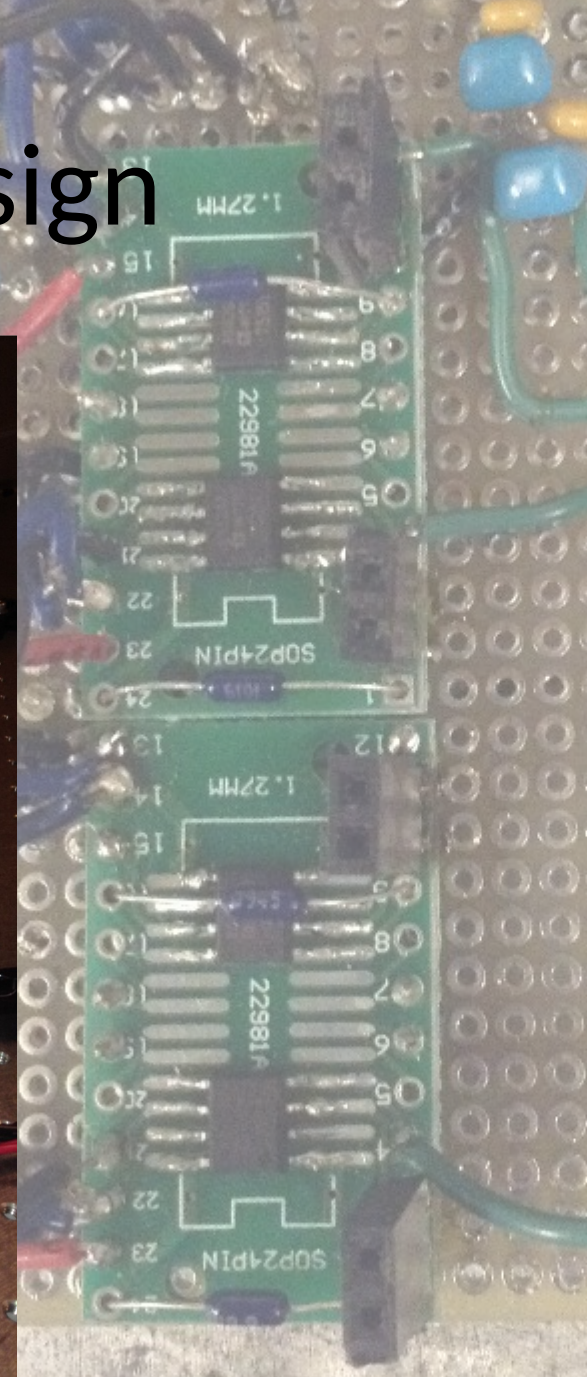
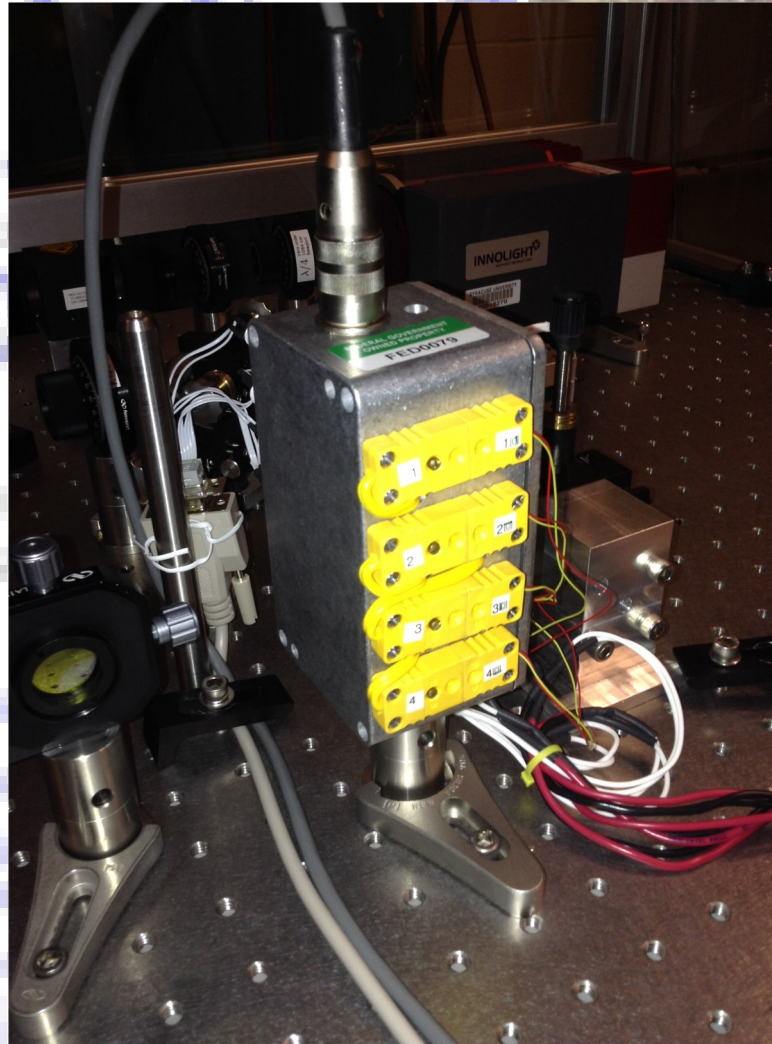
VIEW FROM BOTTOM



Material: 6061 Alloy
We need 1 of these to

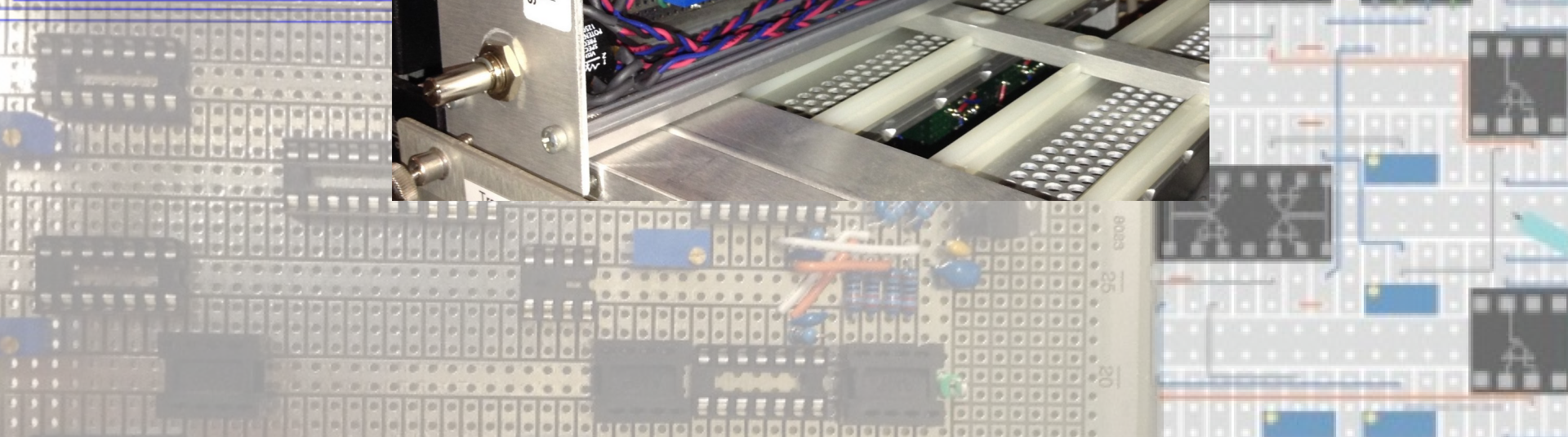
Design modified by
Fabian Magaña-Sando
from DCC Documents
D0901581
D0901582
D0901583

Thermal sensor design



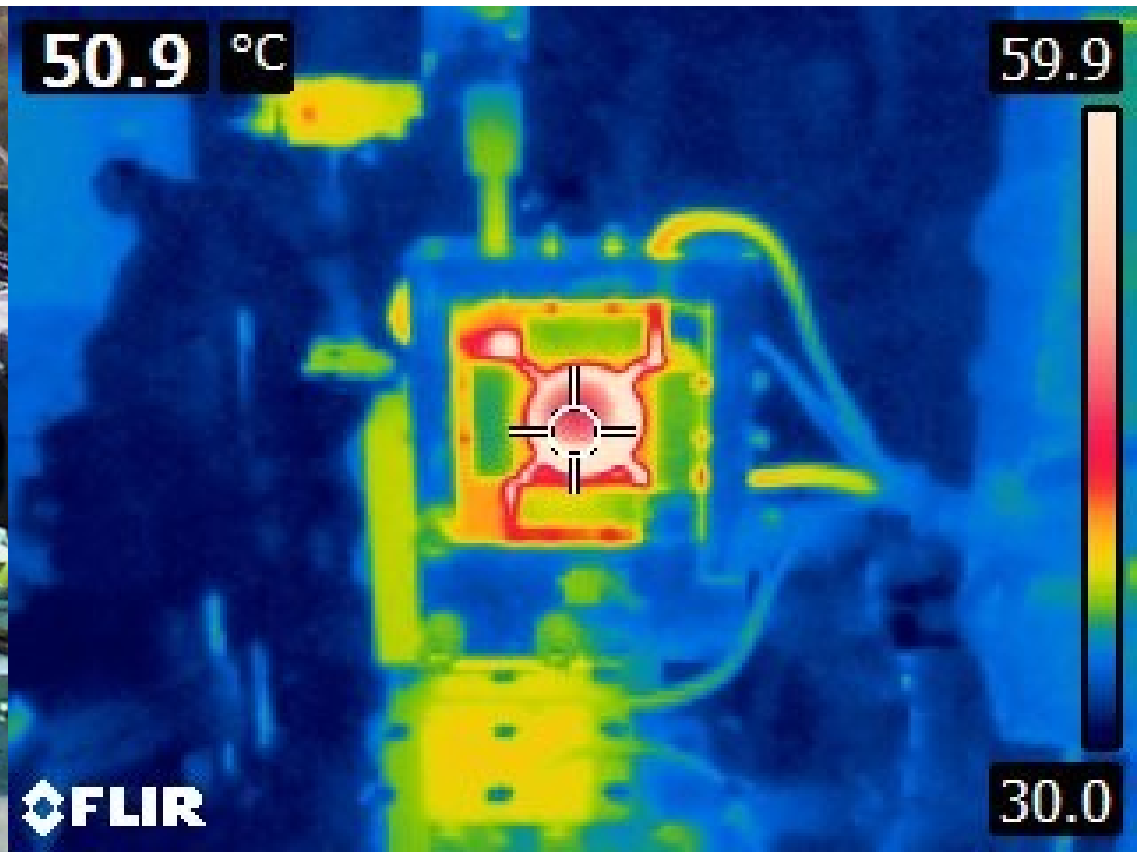
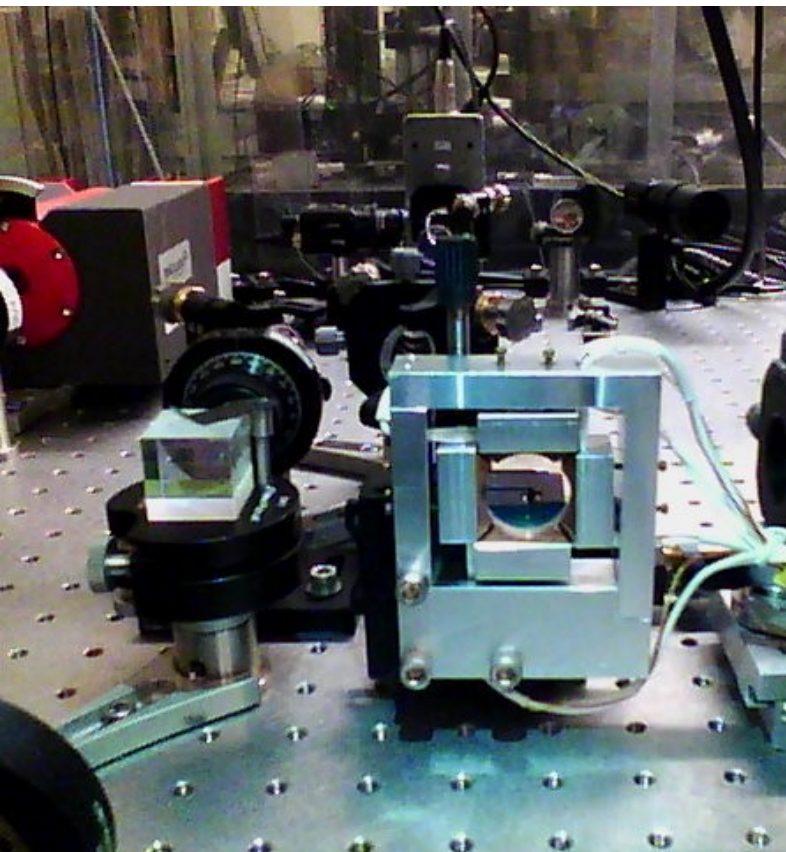
Driver design

The image displays a custom electronic driver board for a thermal lens actuator, mounted in a metal enclosure. The board is populated with various components including integrated circuits, resistors, capacitors, and a ribbon cable. A label on the front panel reads "SYRACUSE UNIVERSITY 20019887". The background shows a schematic diagram of the circuit, which includes sections for a Differential Receiver, Safety Shut Off, Schmitt Trigger, Voltage Regulators, and a Buffer. The schematic also includes a note about the importance of the first set of pins.



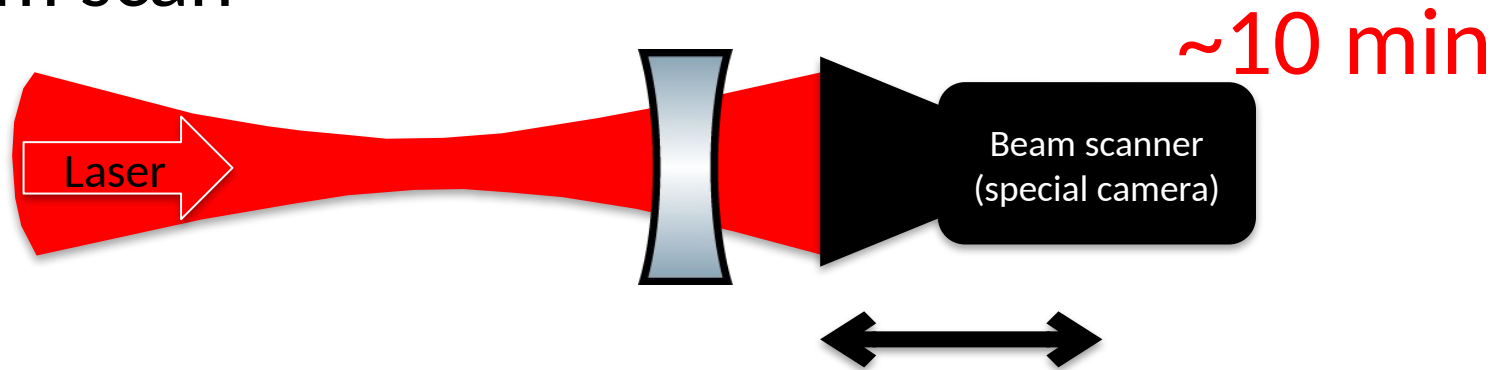


Testing Thermal Actuator

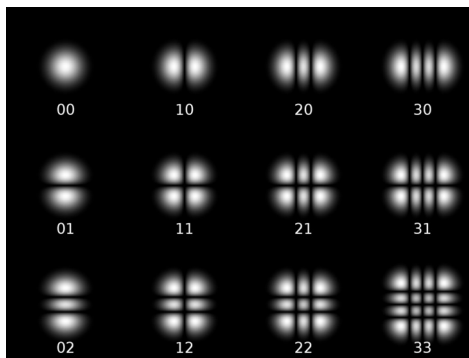


How to measure focal power

- Beam scan



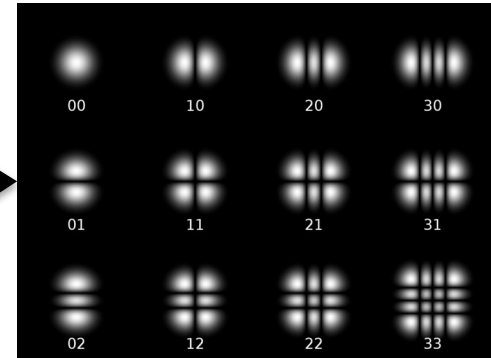
- Transverse mode spacing due to intentional misalignment



~1 sec

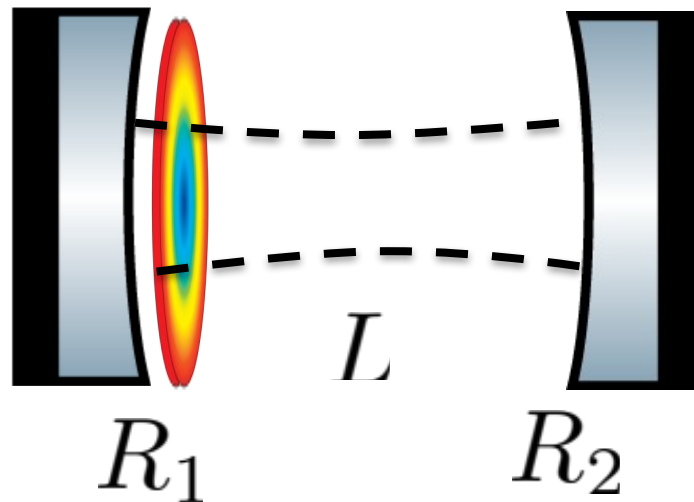
Fabry-Pérot cavity transverse mode spacing

$$f_{TM} = \frac{FSR}{\pi} \arccos \sqrt{g_1 g_2} \longrightarrow$$



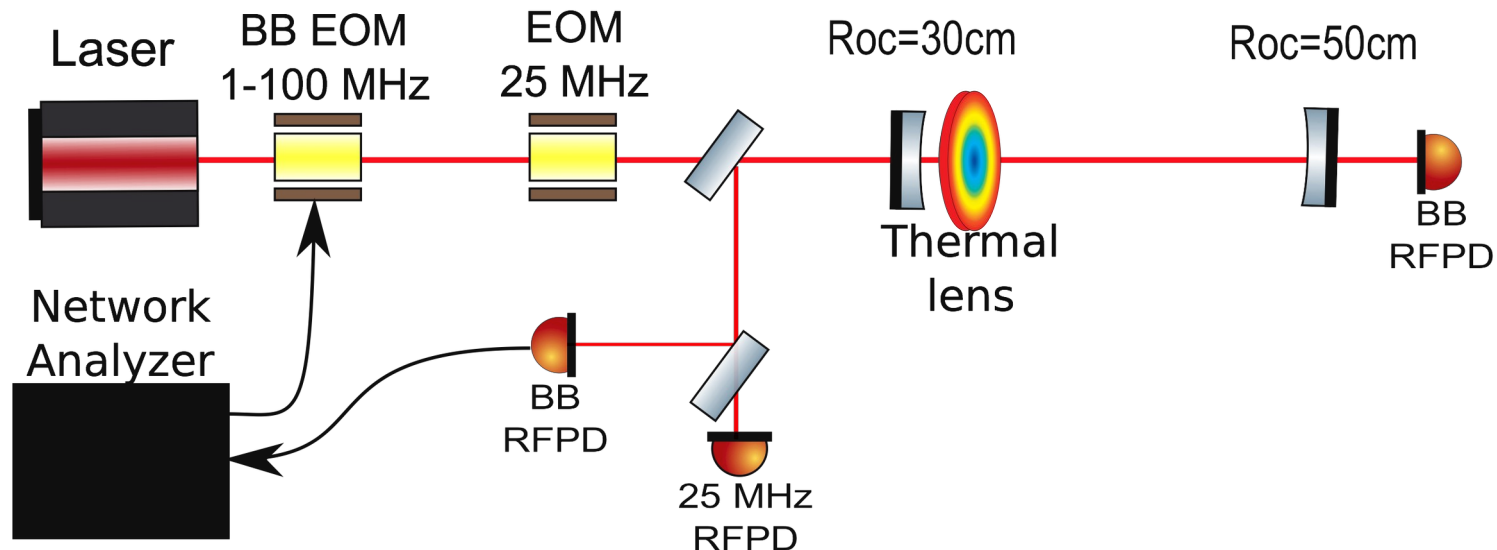
$$FSR = \frac{c}{2L}$$

$$g_{1,2} = 1 - \frac{L}{R_{1,2}}$$

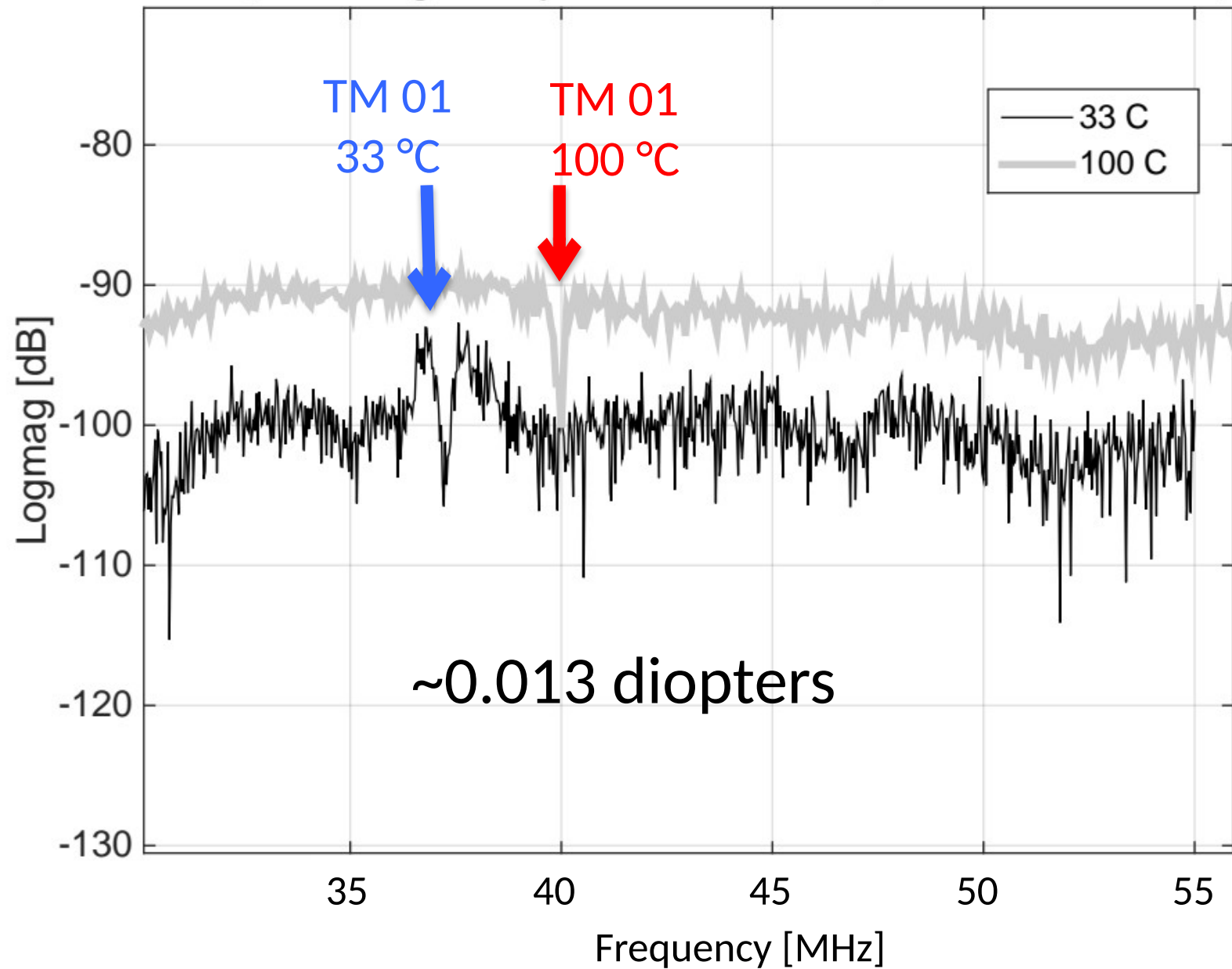


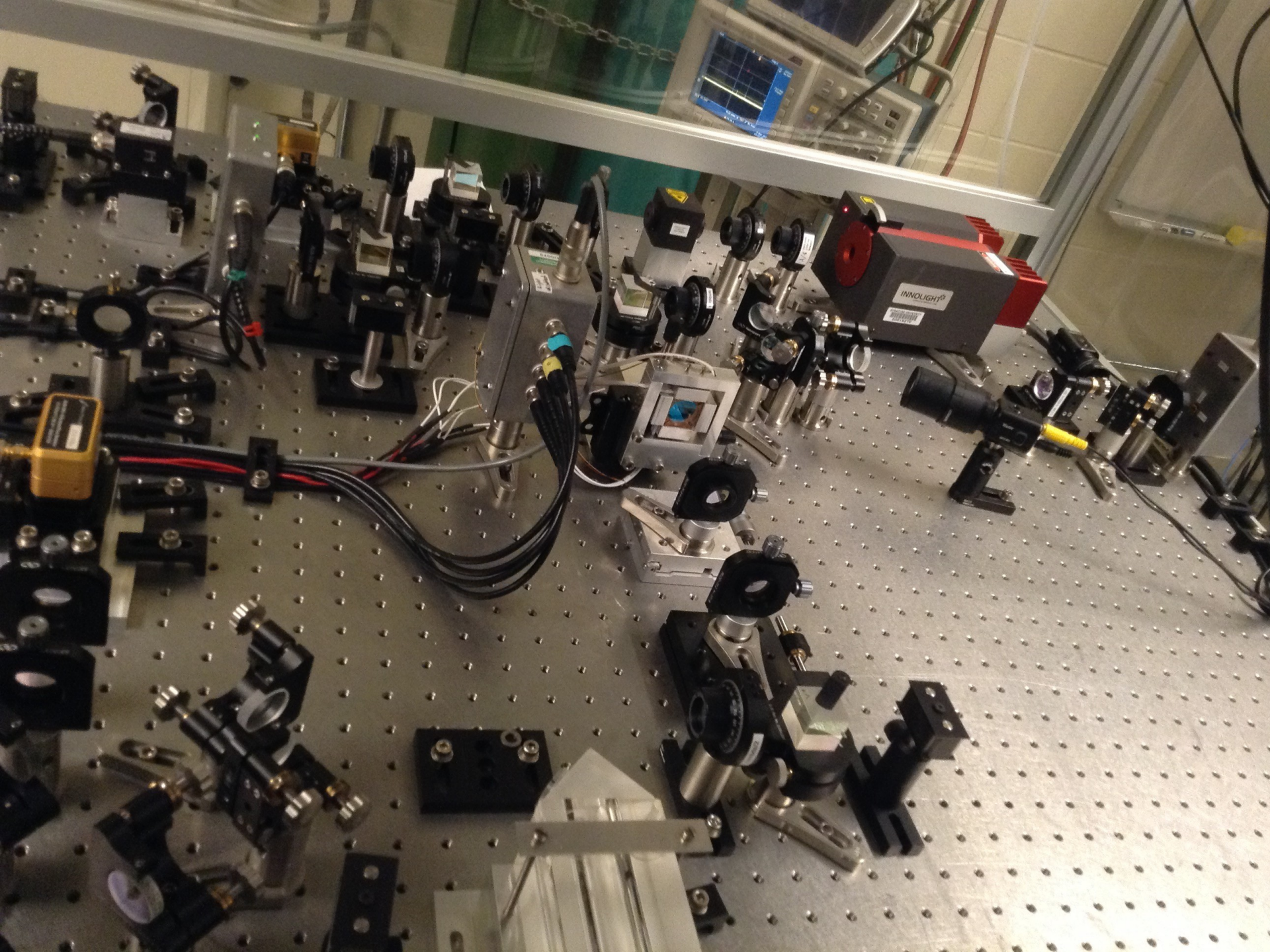
Measuring Focal Power via Transverse Mode Spacing

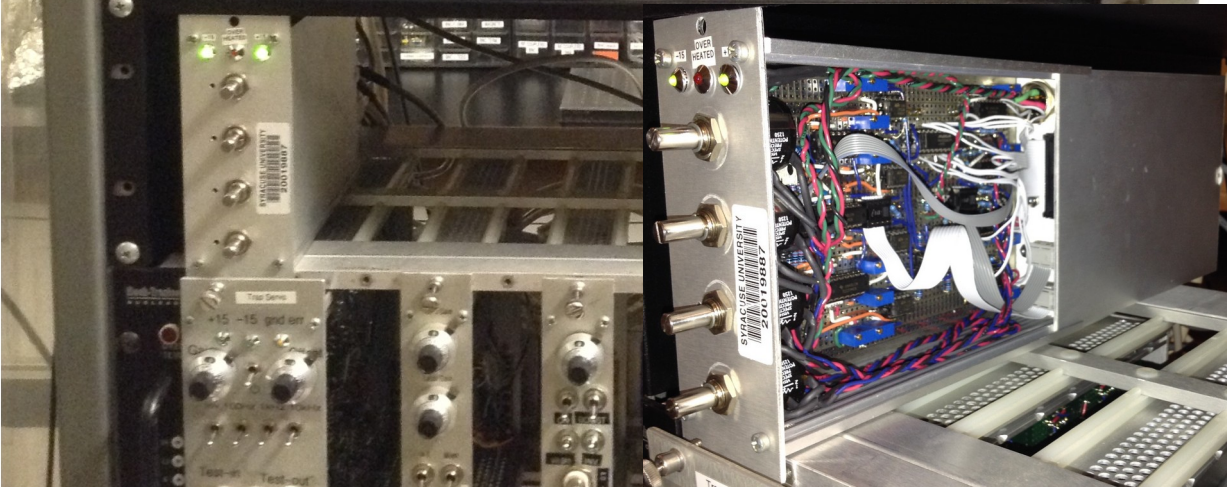
- Lock a ~ 1 meter cavity
- Inject a swept sine (1-100MHz) signal
- Slightly misalign cavity
 - observe the shift of TM spacing due to thermal lens
- Back calculate focal power from TM spacing



Refl BB RFPD, EOM signal injection 1-100MHz, Thermal Lens on, Fans off







Future work

- Vacuum testing
- Waste heat solutions
- Gain more experience with SU AMM setup
- Integration
 - Best placement MM per heating power
 - Best placement for astigmatism correction
- Global optimization of the whole system
 - Include, focal power, mode matching, waste heat,... bad and good things.



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