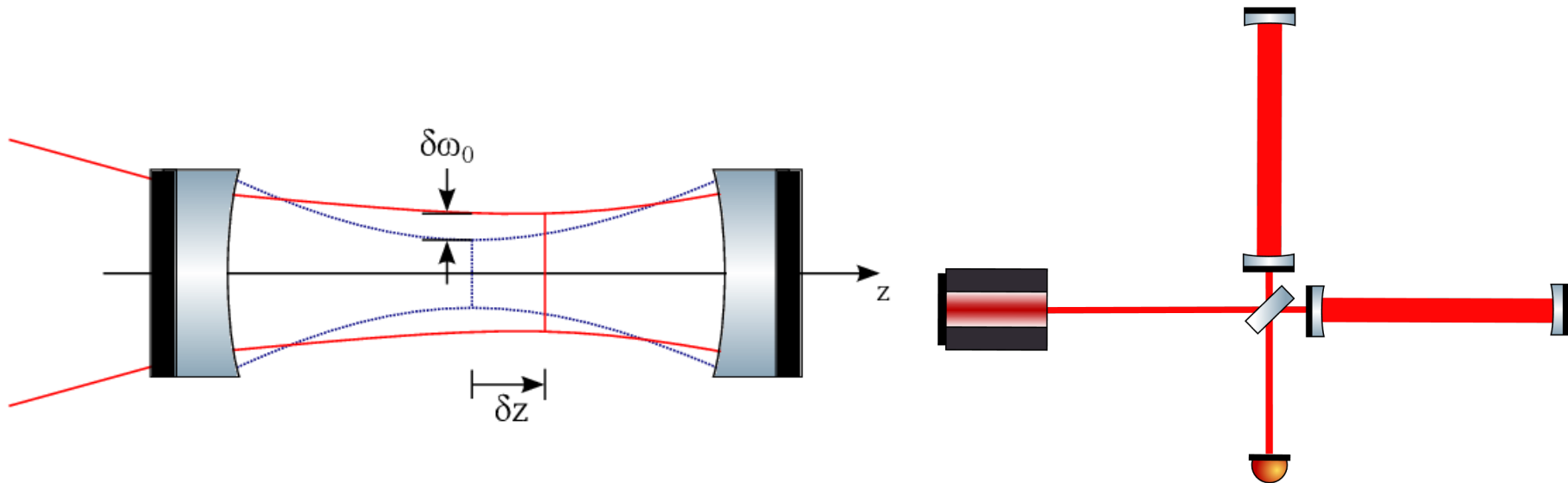


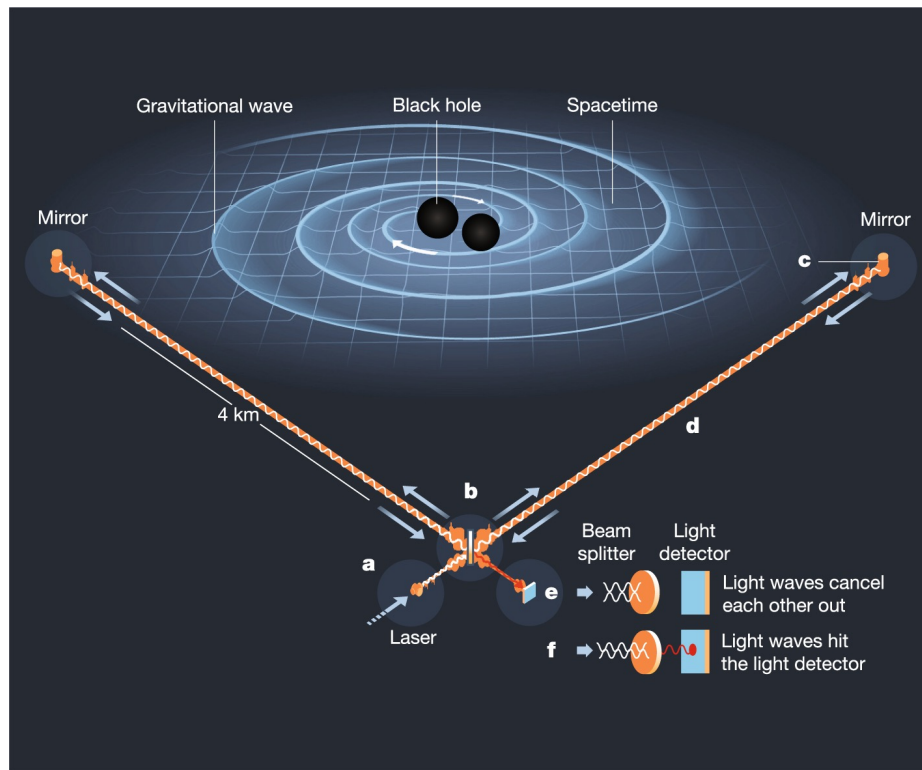
Demonstrating Transverse Mode Control in Gravitational Wave Detectors



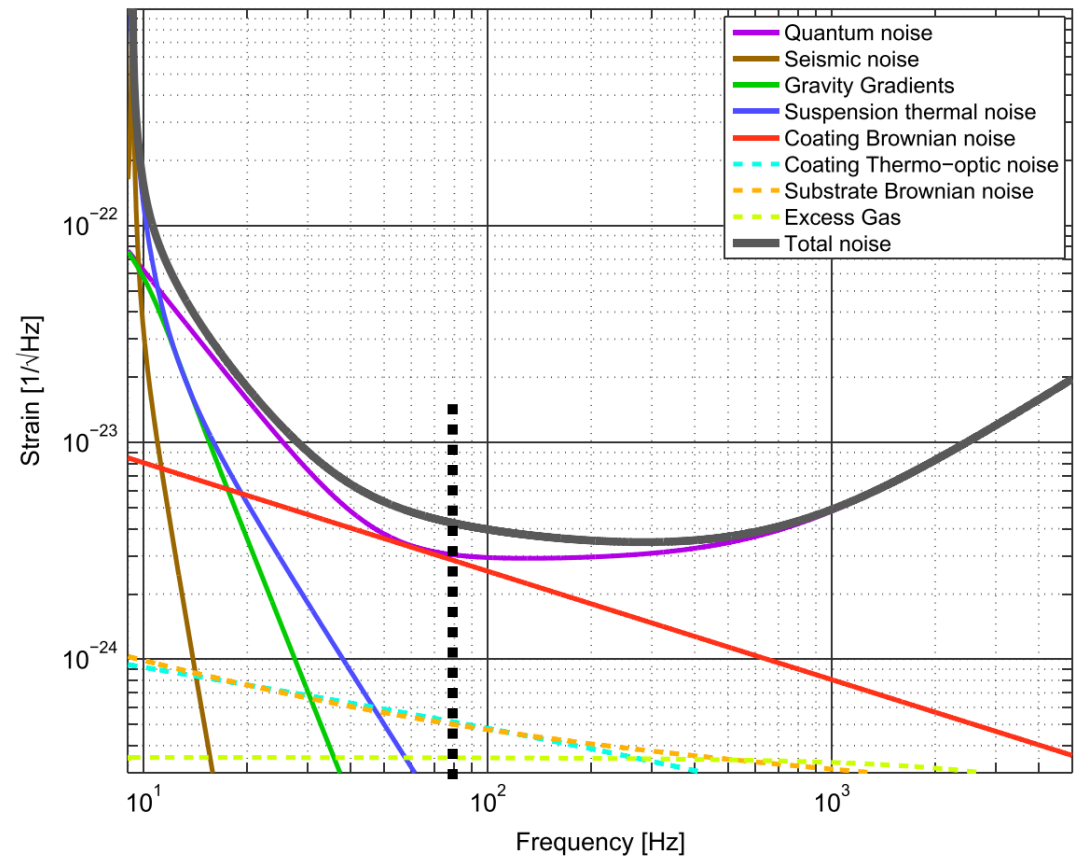
Swapnil Dhage

Aaron Goodwin-Jones, Charlotte Bragard, Clément Lauzin,
Giacomo Bruno, Ricardo Cabrita

What are Gravitational Waves and detectors ?



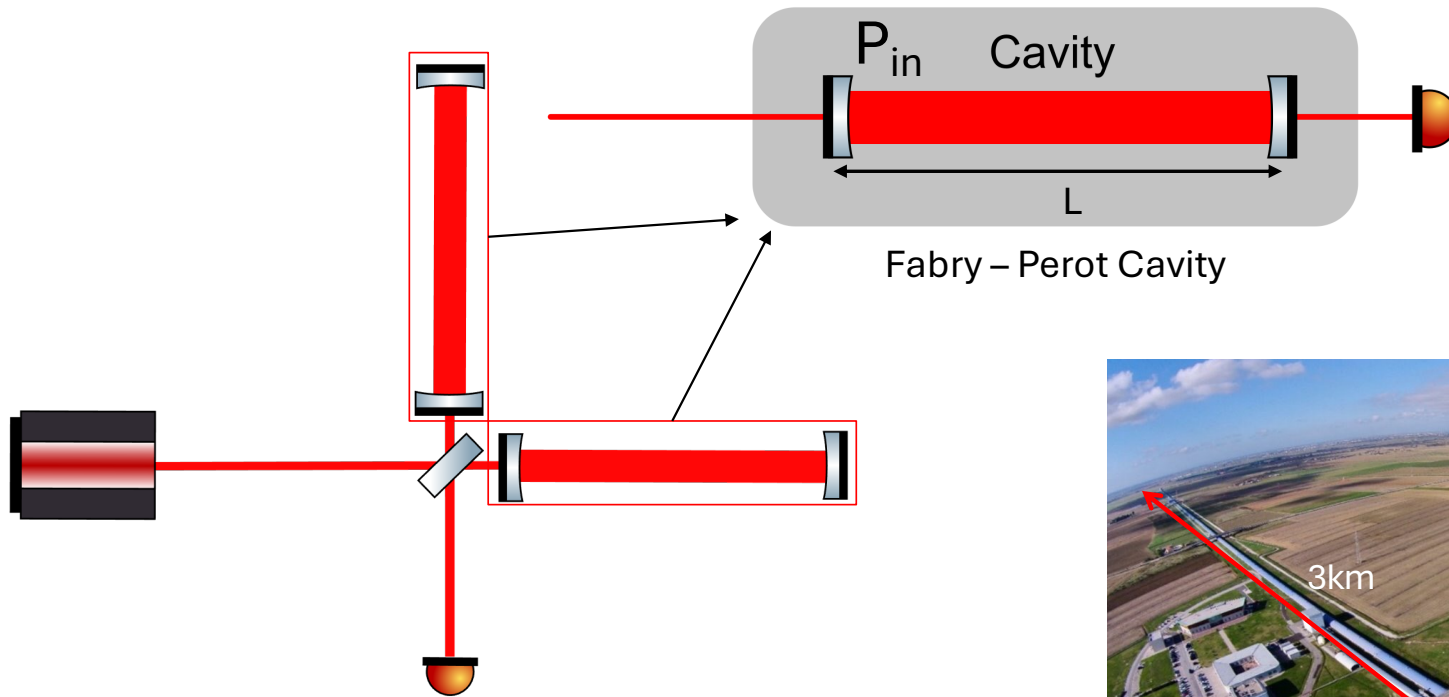
Schematic of gravitational-wave detection with a Michelson interferometer¹.



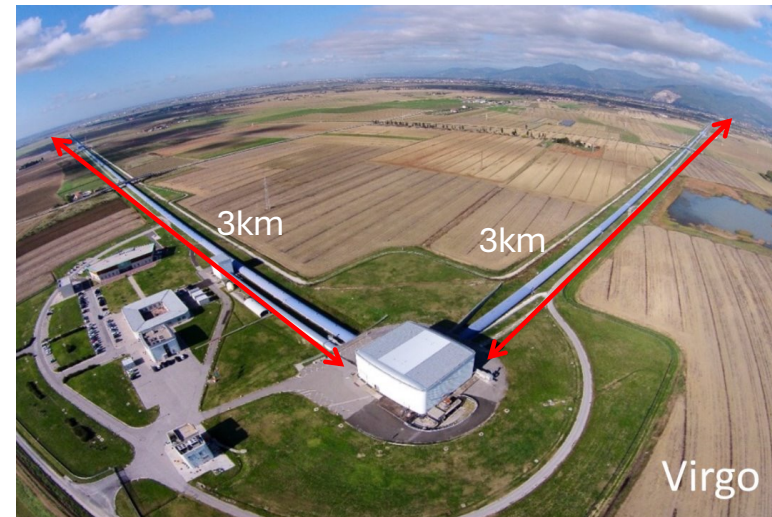
Sensitivity curve of Advanced LIGO detector

1. Miller, M.C., Yunes, N. The new frontier of gravitational waves. *Nature* **568**, 469–476 (2019). <https://doi.org/10.1038/s41586-019-1129-z>

Optical Cavities

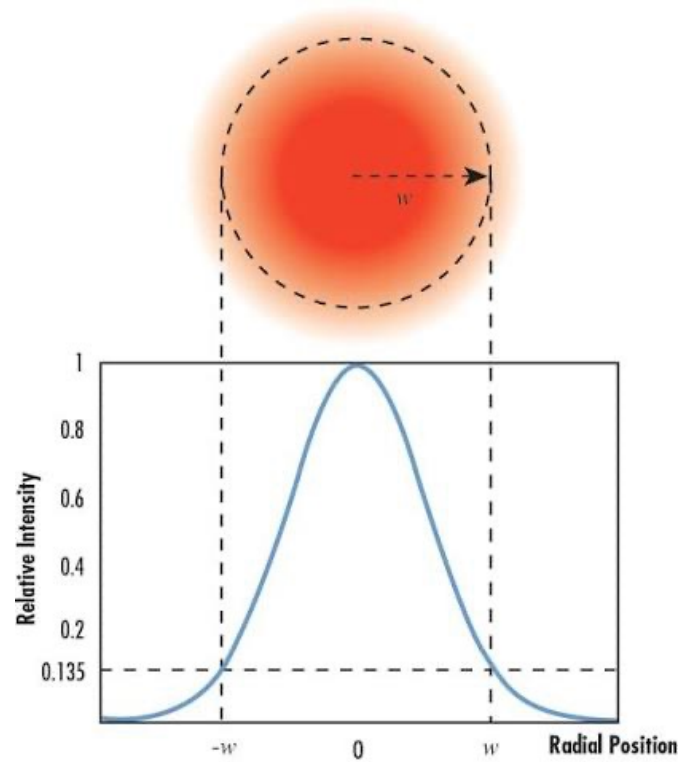


Schematic of a gravitational wave detector with optical cavity in each arm.

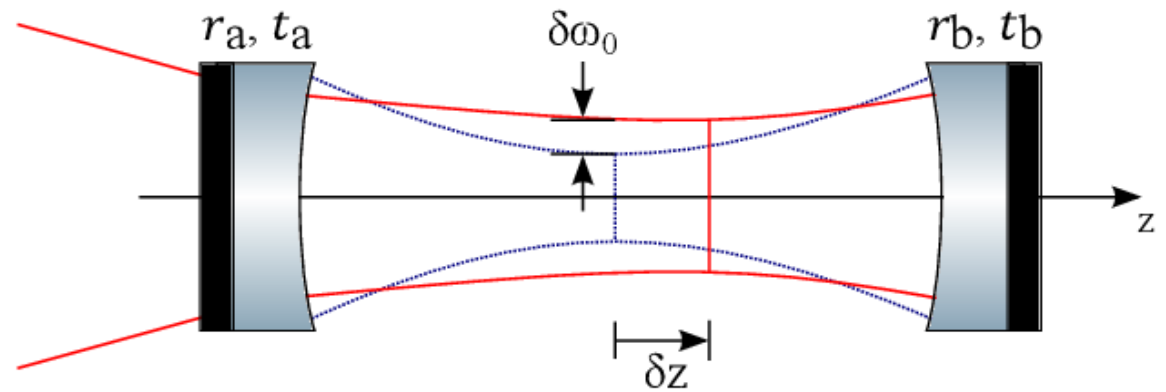


VIRGO Interferometer

Transverse Mode



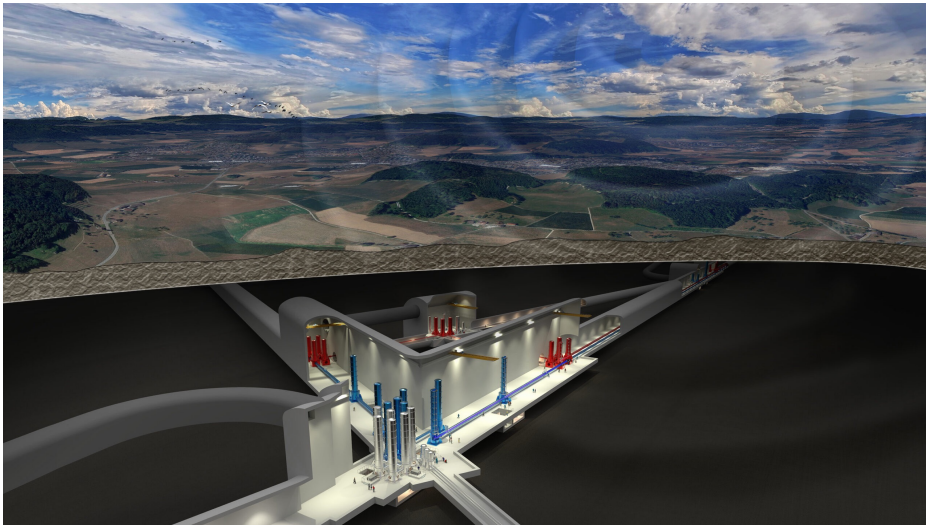
Gaussian beam profile¹



Mode mismatch in an optical cavity with blue line depicting cavity eigenmode and red line depicting shape of beam inside cavity²

1. Edmund Optics. (n.d.). *Gaussian beam propagation*. Retrieved September 21, 2026, from <https://www.edmundoptics.com/knowledge-center/application-notes/lasers/gaussian-beam-propagation/>
2. Miller, J., & Evans, M. (2014). Length control of an optical resonator using second-order transverse modes. *Optics Letters*, 39(8), 2495. <https://doi.org/10.1364/ol.39.002495>

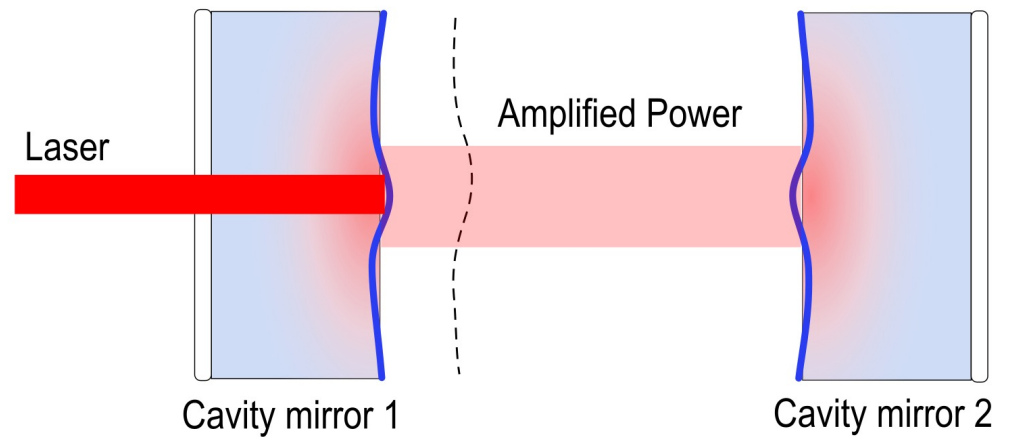
Limitation of Future GW Detectors



Einstein Telescope¹

High Power in optical cavities is limited due to thermal distortions of cavity mirrors

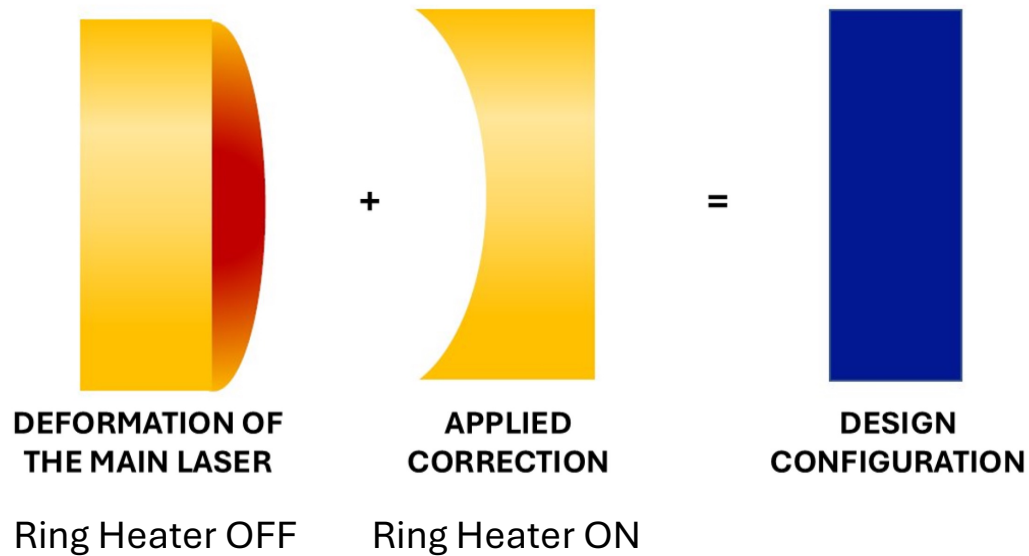
Detectors	LIGO	VIRGO	ET-HF
Arms Circulating Power	350 kW	96 kW	3000 kW (In future)



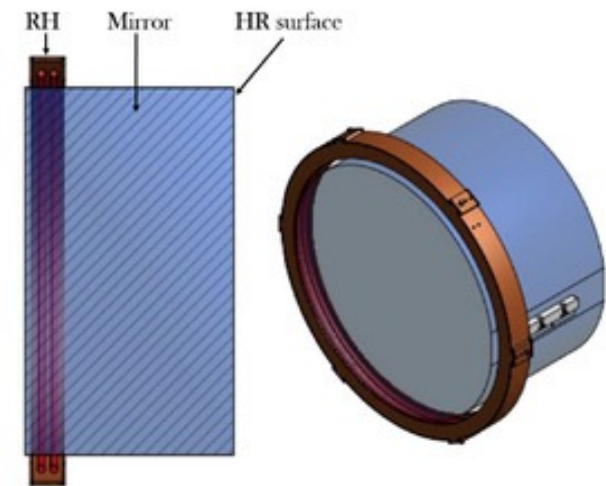
Thermal distortions in an optical cavity

1. <https://einstein Telescope.eu/multimedia-resources/images/>

Thermal Compensation system(TCS)



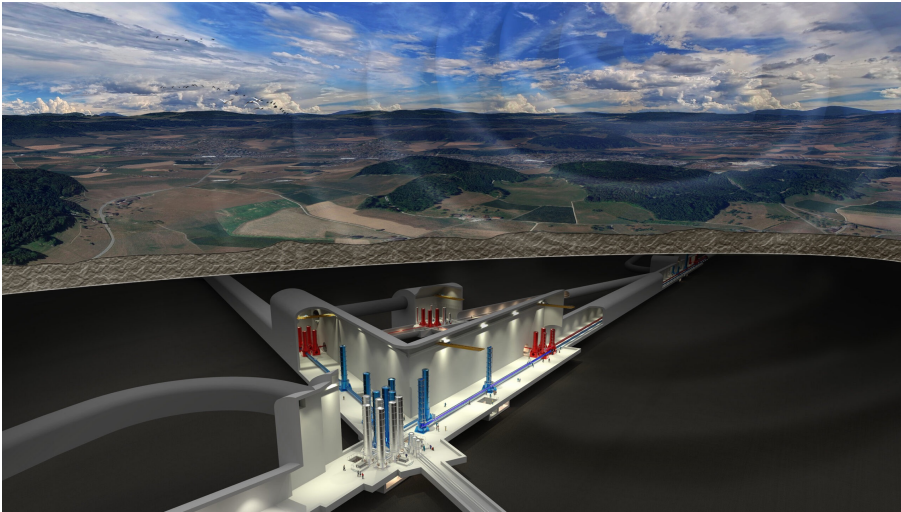
Schematic representation of the TCS principle of operation¹



CAD drawing of the RH surrounding a mirror.¹

1. Cifaldi, M., Taranto, C., Aiello, L., & Lumaca, D. (2025). Adaptive Optics for Aberration Control in Einstein Telescope. *Galaxies*, 13(2), 18. <https://doi.org/10.3390/galaxies13020018>

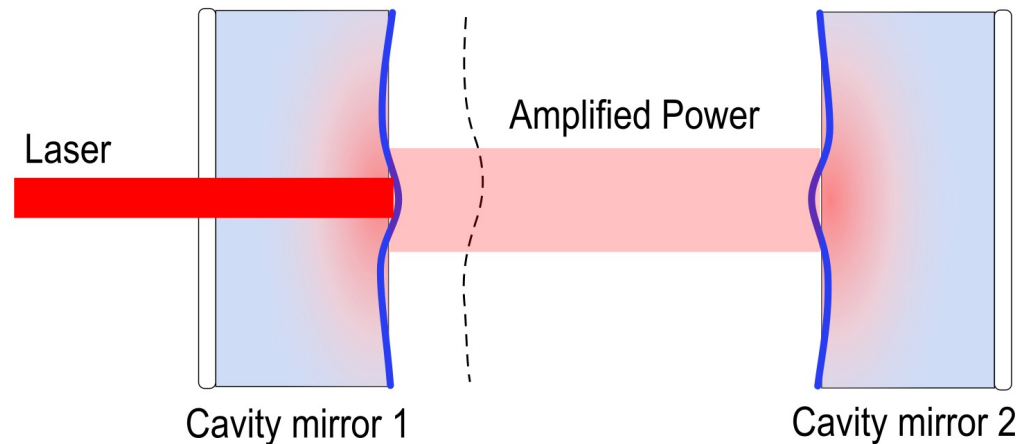
Limitation of Future GW Detectors



Einstein Telescope

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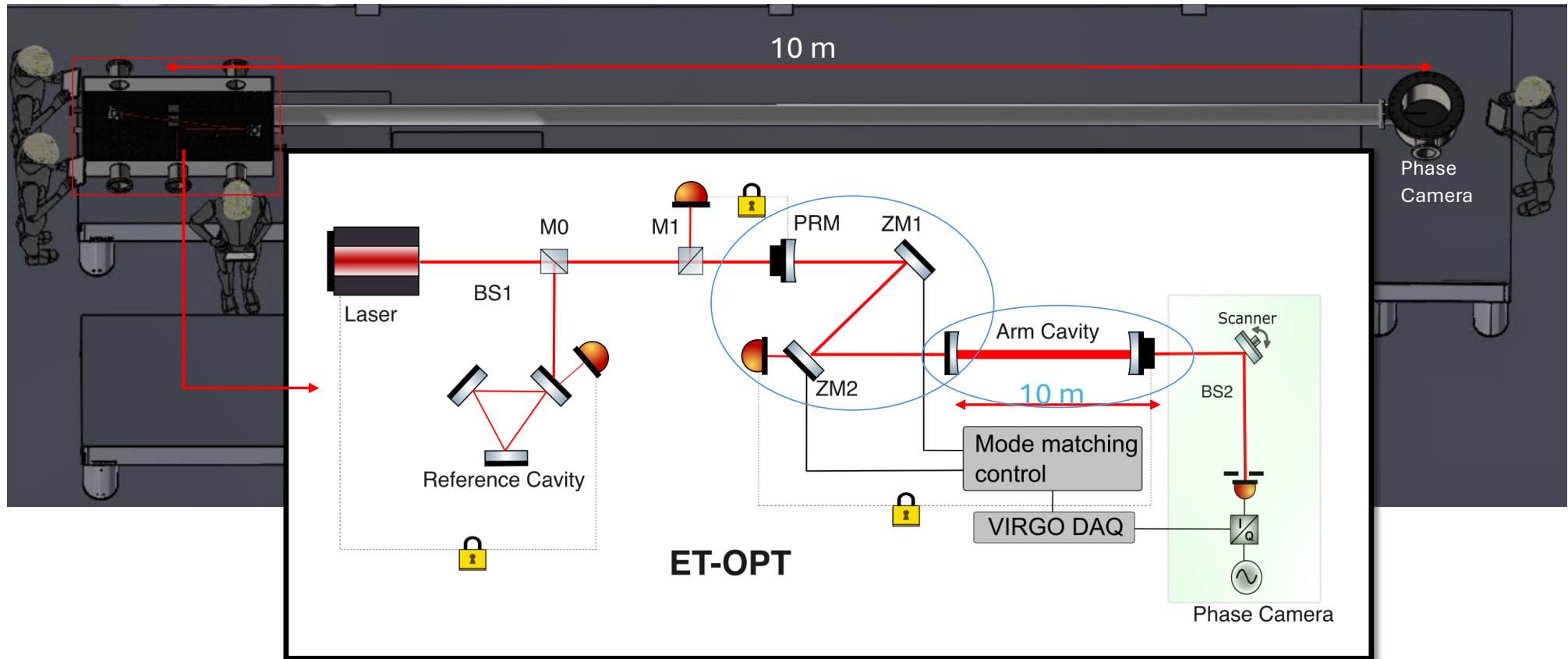
Arms Circulating Power	LIGO	VIRGO	ET-HF
Design	750 kW	150 kW	3000 kW
Actual	350 kW	96 kW	~



Thermal distortions in an optical cavity

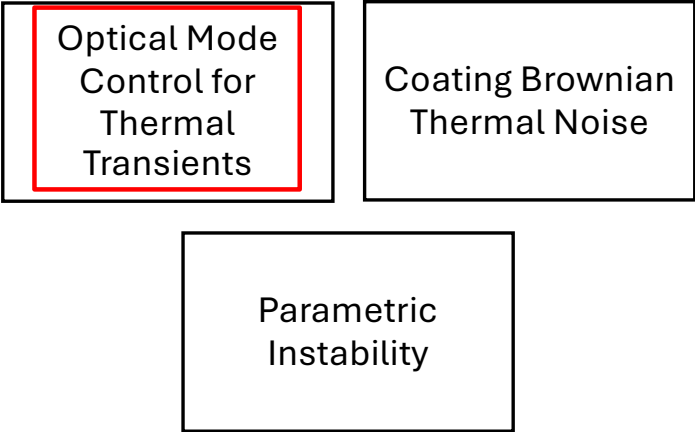
Demonstrating Transverse Mode Control

ET-OPT : 10 m Prototype (Aaron's Talk on ET-OPT tomorrow)

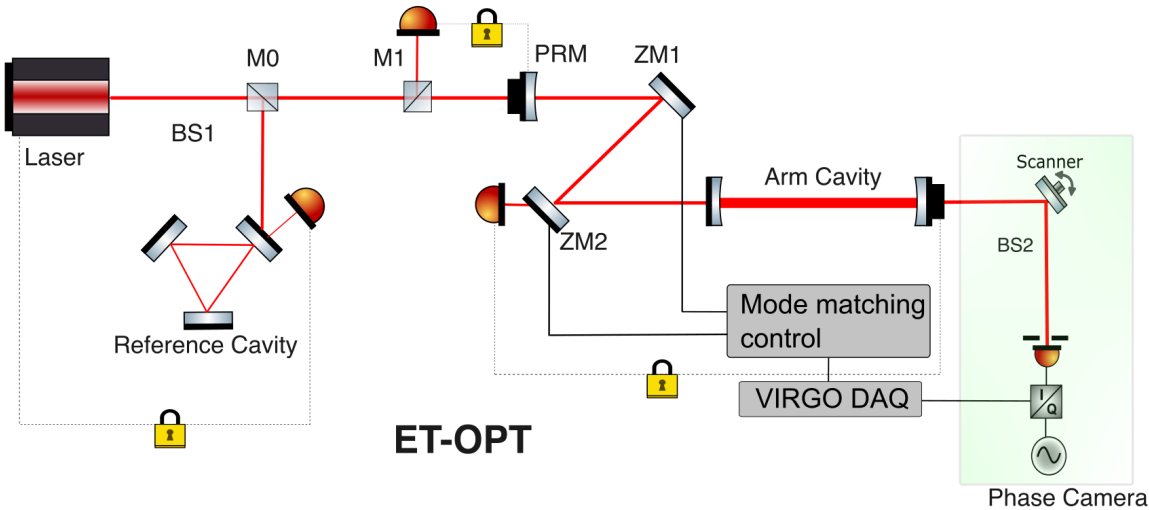


ET-OPT Optical Layout

ET-OPT vs ET-HF



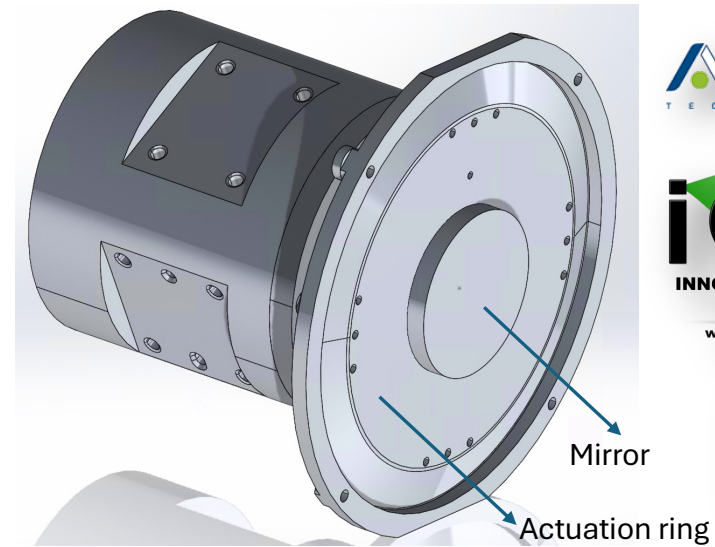
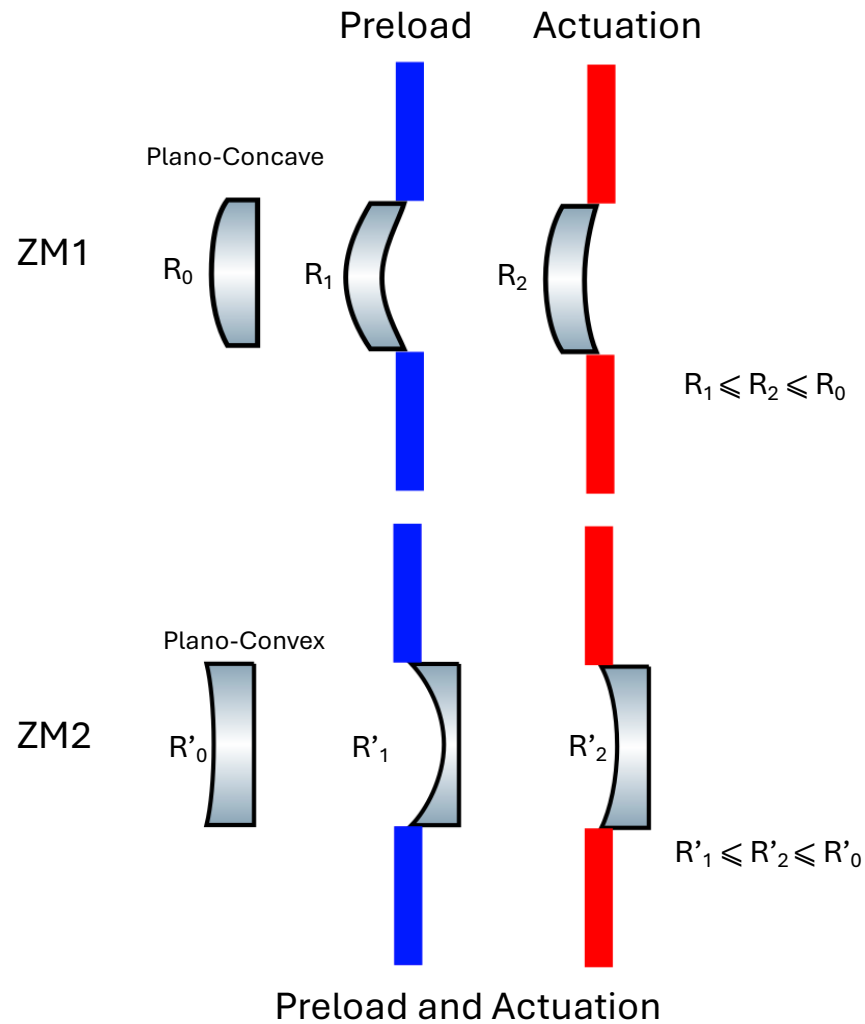
Parameters	ET-HF	ET-OPT
Cavity Length	10000 m	10 m
g-factor (g_1g_2)	0.9455	0.9455
Finesse	101.5	101.5
Power density	13.16 kW/cm ²	13.16 kW/cm ²
Radius of Curvature	5070 m	5.07 m
Circulating Power	3 MW	3 kW
FSR	14.99 kHz	14.99 MHz
Linewidth (FWHM)	147.7 Hz	147.7 kHz
Mode spacing / FSR	92.5 %	92.5 %



ET-OPT

ET-OPT Optical Layout

TSAMS

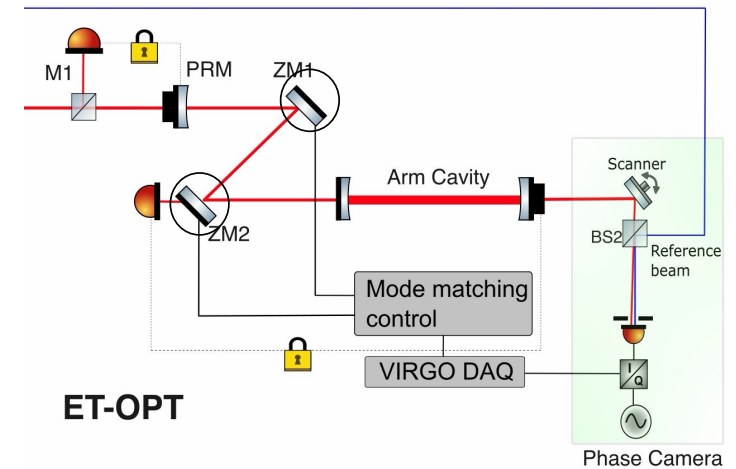


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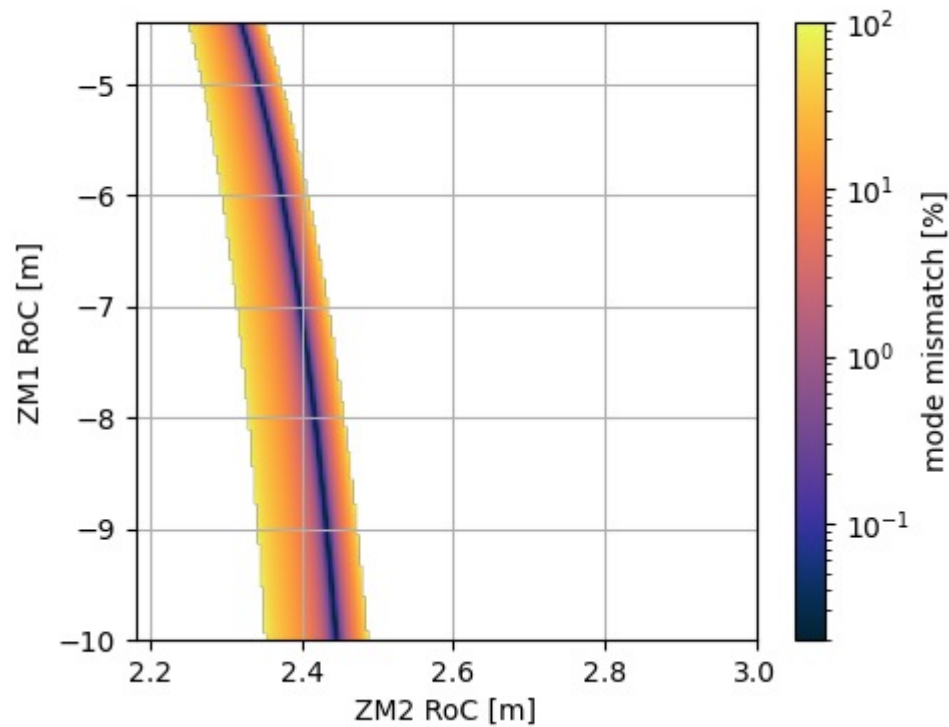
TSAMS CAD Model, based on University of Adelaide design¹



Schematic of Coupled Cavities of ET-OPT

1. Cao, H. T., Ng, S. W. S., Noh, M., Brooks, A., Matichard, F., & Veitch, P. J. (2020). Enhancing the dynamic range of deformable mirrors with compression bias. *Optics Express*, 28(26), 38480. <https://doi.org/10.1364/oe.408921>

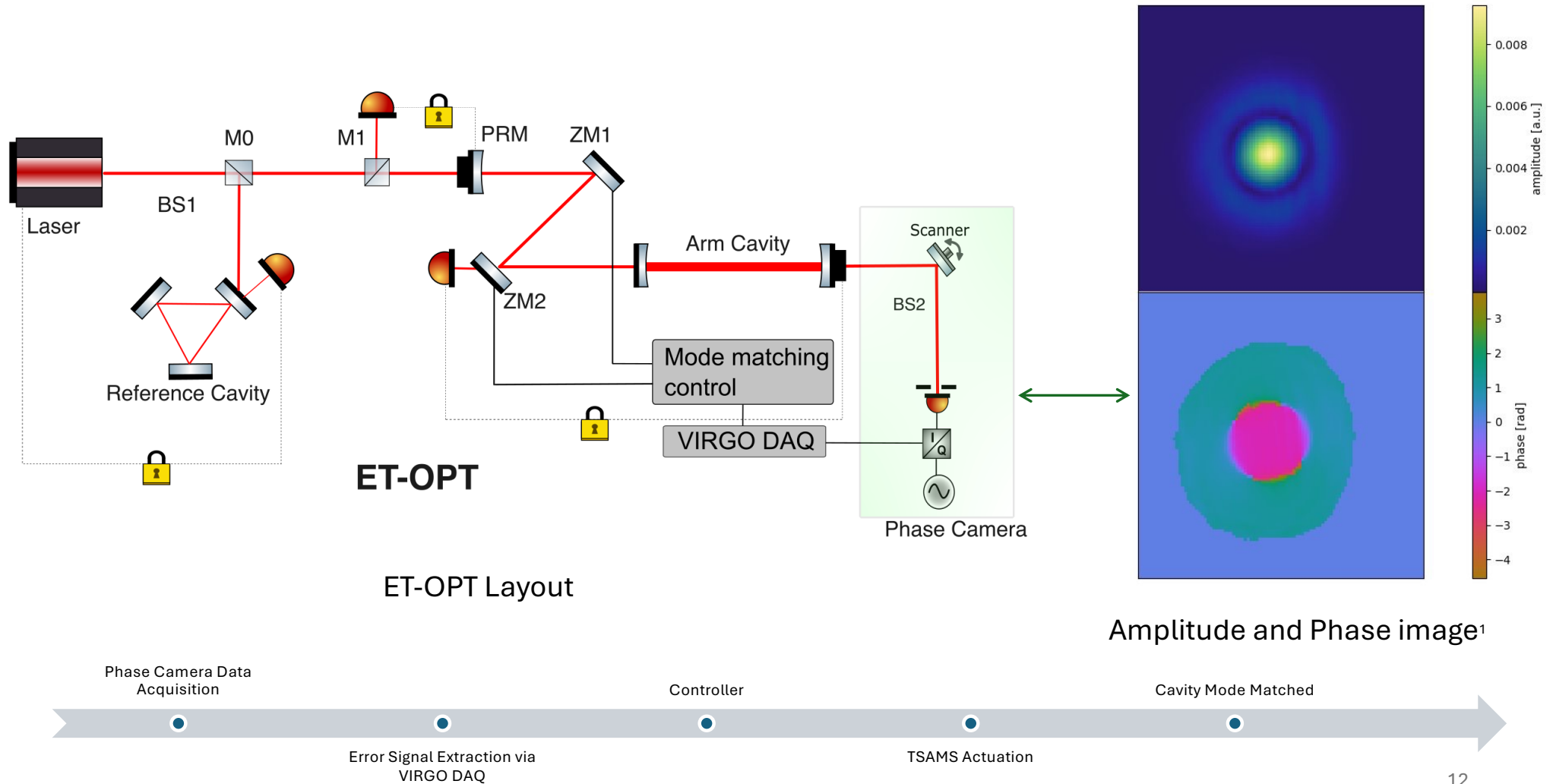
TSAMS Mode Matching Landscape



- ZM2 has more stringent requirements
- Operating point :
 - ☐ setting ZM1 to a certain value
 - ☐ scanning ZM2 for mode matching

Mode mismatch for change of RoC of ZM1 and ZM2

Closed Loop Mode Matching Control



1. Mode sensing with the phase camera for gravitational-wave interferometers Doctoral dissertation presented by Ricardo de Abreu Silvério Cabrita



Thank you
Questions ?

Back up Slides

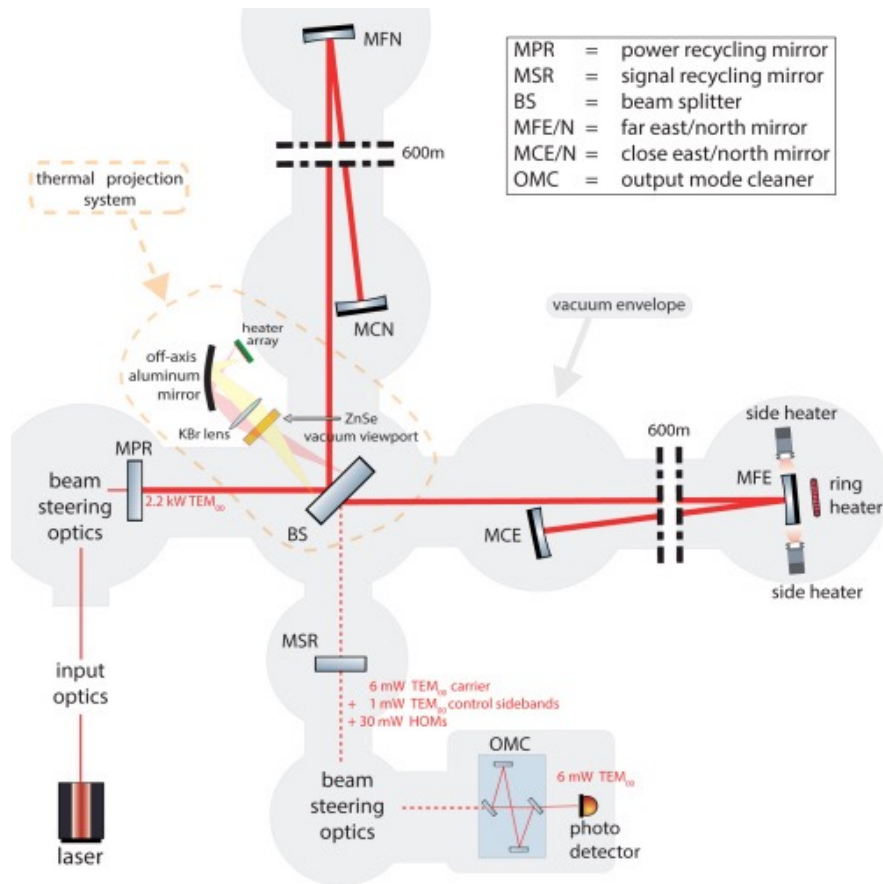


Figure : Optical Layout of GEO600

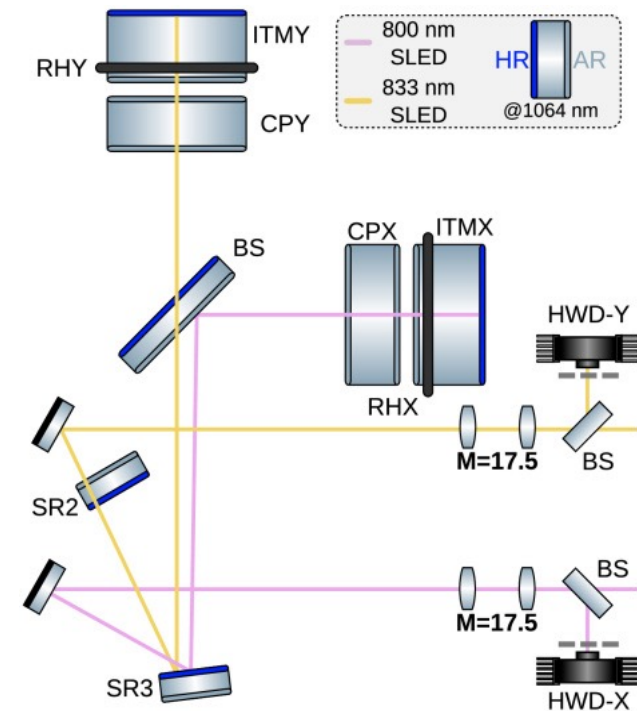
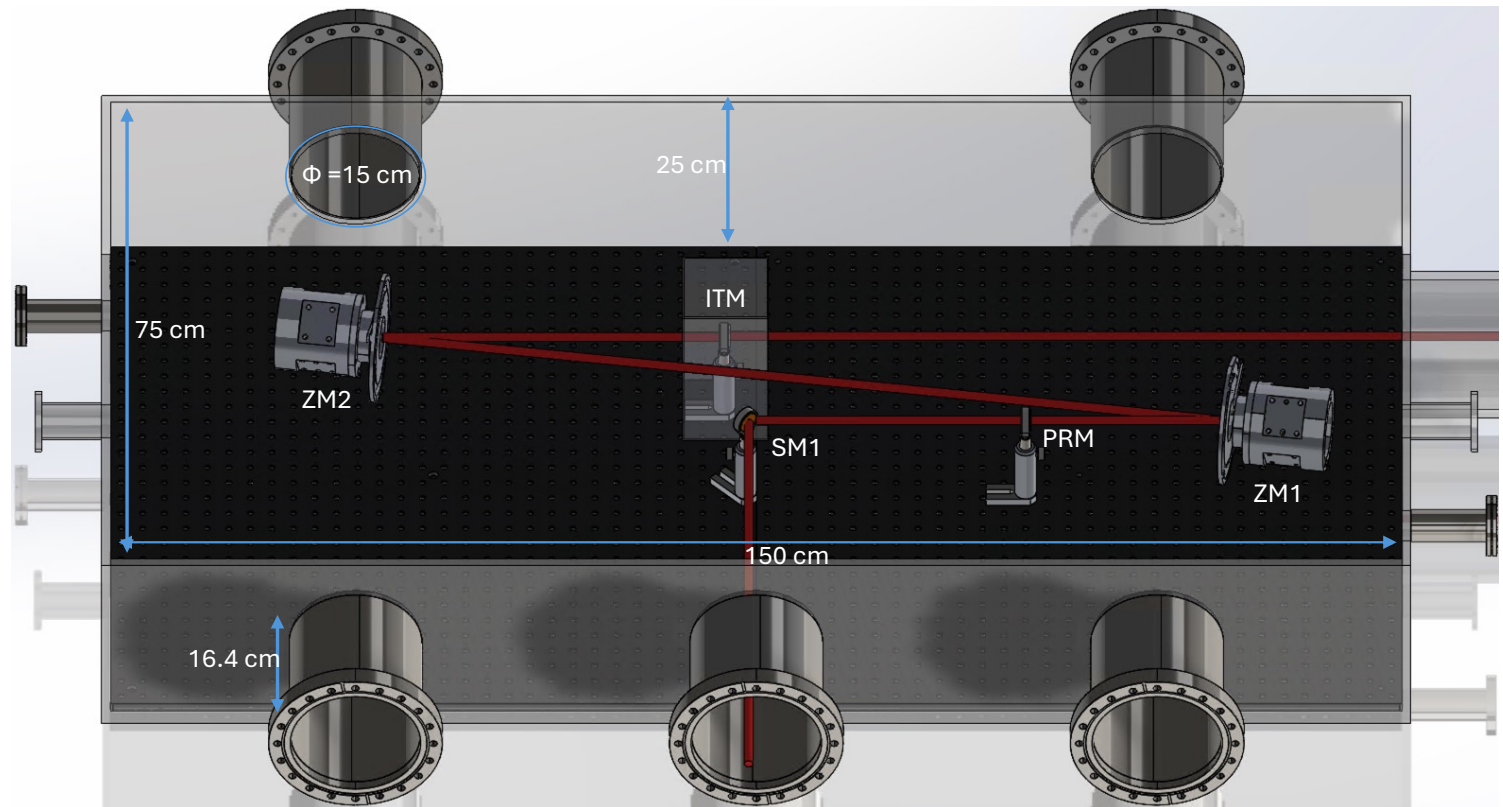


Figure : Schematic representation of the Advanced LIGO wavefront sensors

ET-OPT Vacuum system

- Operating Pressure = 10^{-7} mbar
- Material = Stainless steel
- Volume = 281.250 L
- Operating Temperature = 293 K
- Outgassing rate = 33.75 L/sec



$P_{in} = 400 \text{ kW}$

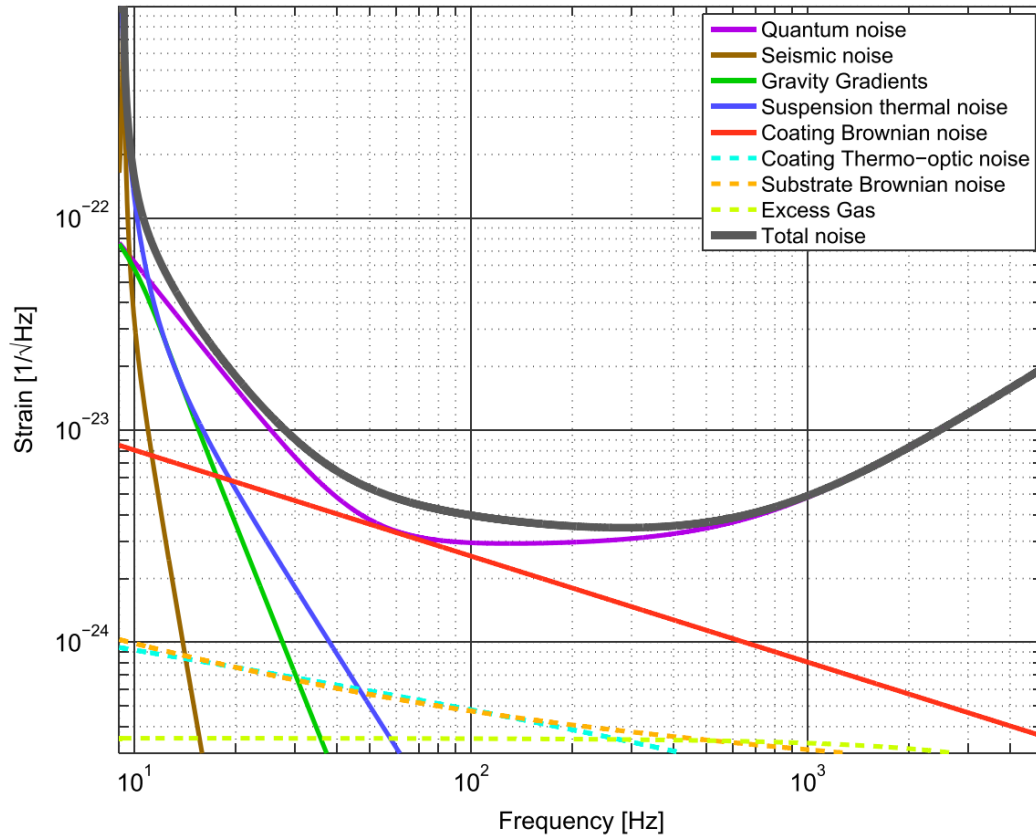


Figure : Sensitivity curve for advanced LIGO

$P_{in} = 3000 \text{ kW}$

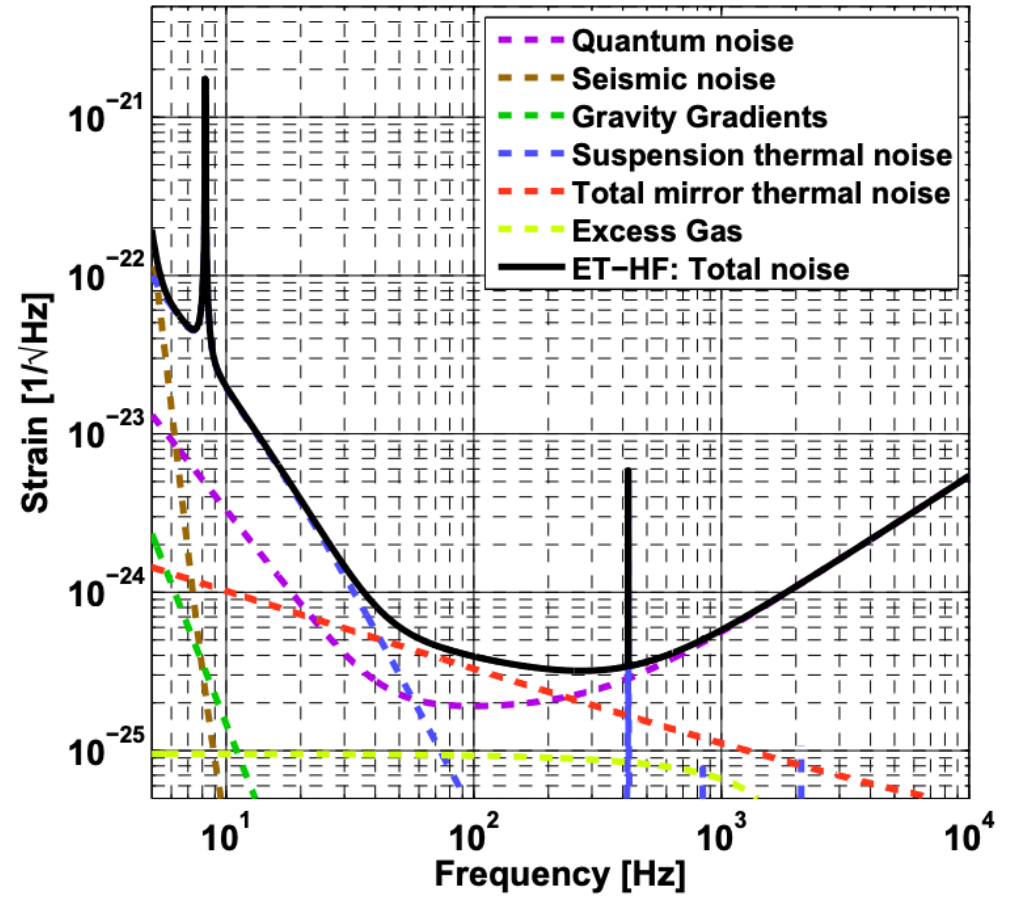
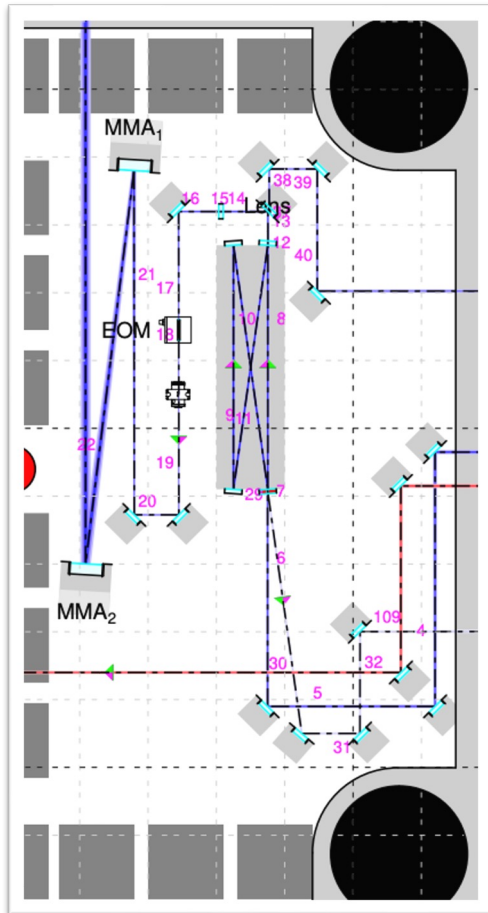
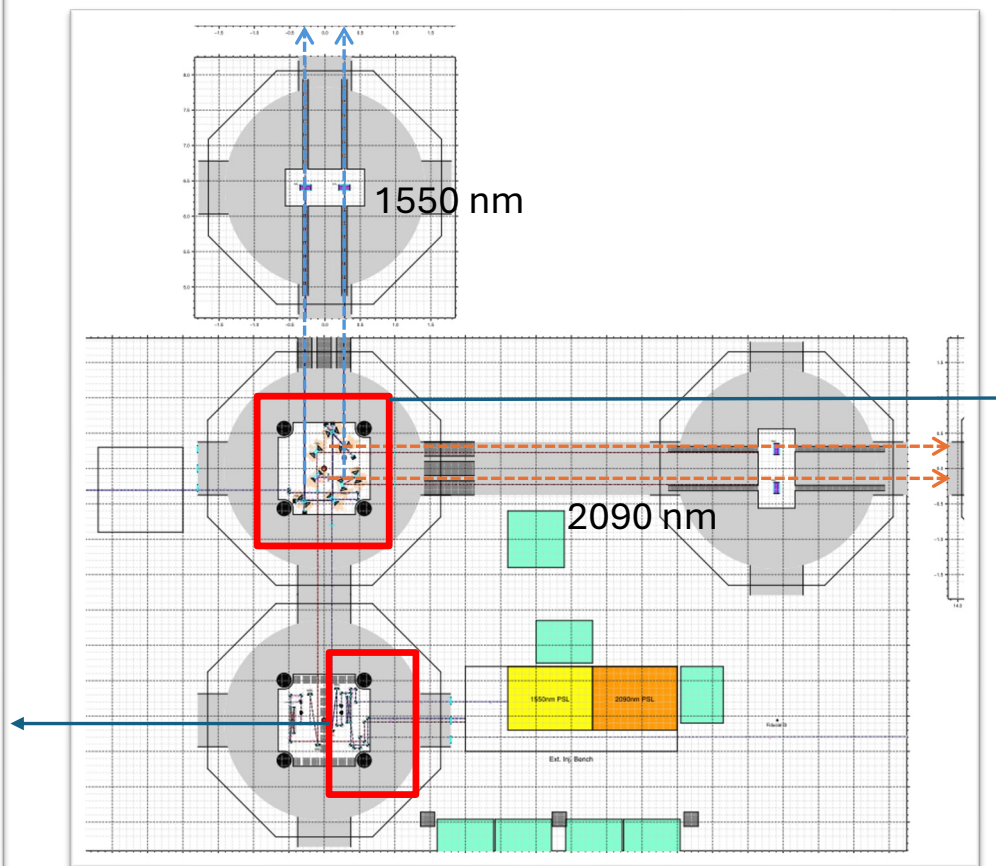


Figure : Sensitivity curve for ET-HF

Mode Matching solution for ETpathfinder(ETpf) (WP2)

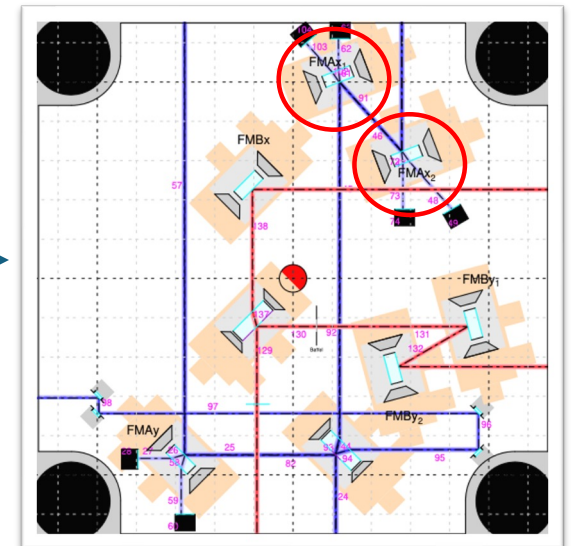


ETpf Optical Layout for 1550 nm



ETpf Layout

Placement of TSAMS



Mode control with TSAMS

- First demonstration of intra-cavity closed loop mode control. Realized with
 - Phase camera
 - TSAMS
- ZM 1 –
 - Initial RoC = -10 m
 - Preload = -4.4 m
 - Mode Matching Set Point = -5.5 m
- ZM 2 –
 - Initial RoC = 3 m
 - Preload = 1.6 m
 - Mode Matching Set Point = 2.183 m

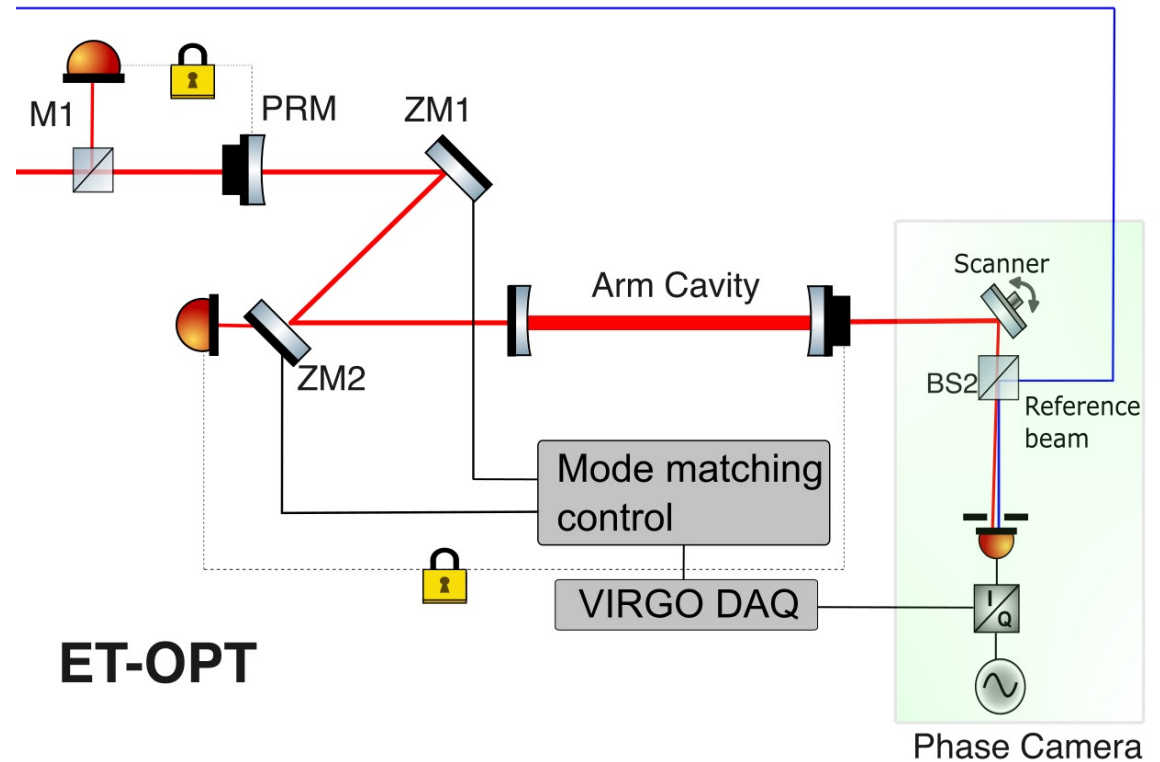


Figure – ET-OPT Optical Setup