Thermal Deformations and Thermal Compensation in Gravitational-Wave Detectors

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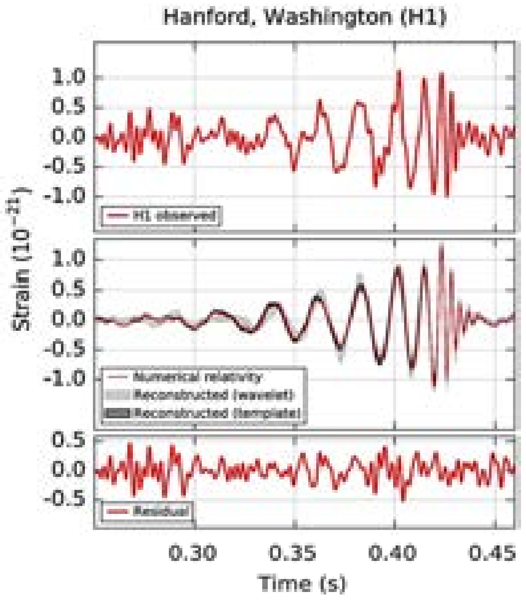
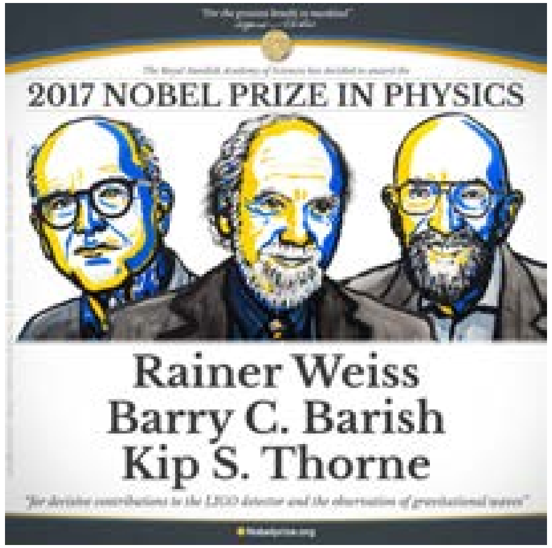
Advanced Virgo

Gravitational Waves

- Created in extremely violent astronomical events, e.g. collisions of such as black holes and neutron stars
- Propagate almost unhindered as ripples through space-time
- Squeeze and stretch space-time as they pass through, but typically to an extremely small amount, of order 10^{-21}
- Predicted by Einstein's General Theory of Relativity in 1915, first detected 100 years later in 2015
- Since then, of order 50 more events detected
- 5 active detectors: LIGO in Livingston and Hanford, USA; Virgo in Cascina, Italy; GEO600 in Ruthe, Germany; KAGRA in Kamioka mine, Japan





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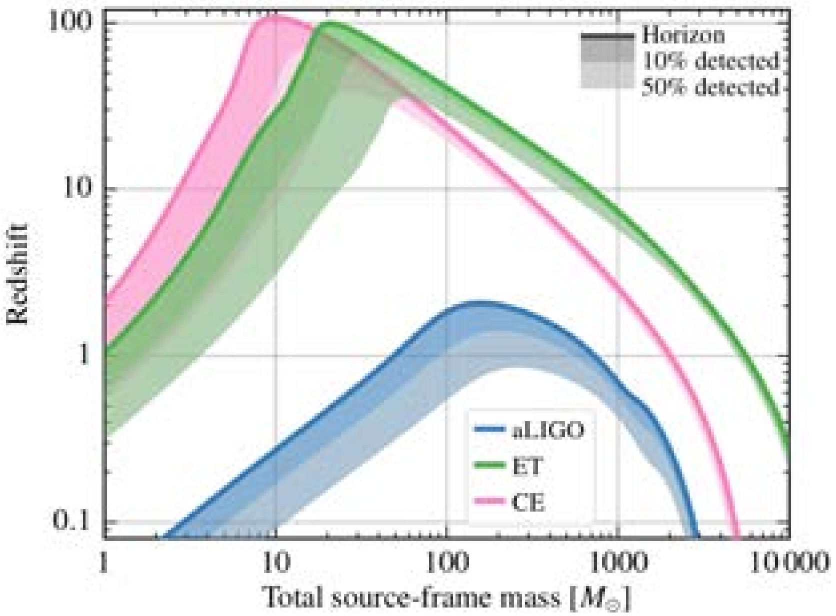
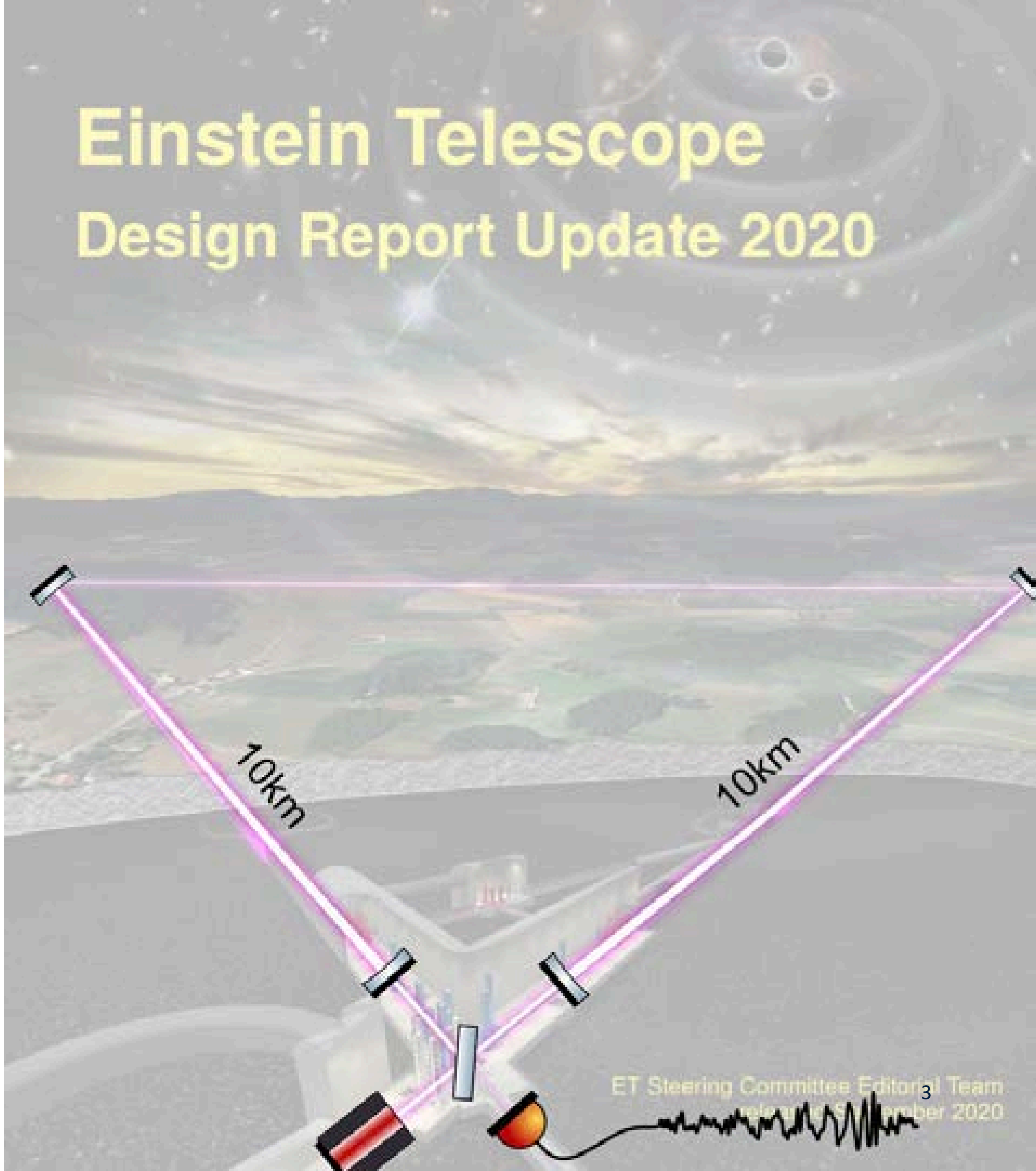
Einstein Telescope

- Current detectors are part of the second generation, a third generation is planned
- Einstein Telescope submitted to ESFRI roadmap
- Projected costs 1.9G€, operational by 2035
- 10km baseline interferometer
- Located underground
- Sardinia or three-border region NL/BE/DE

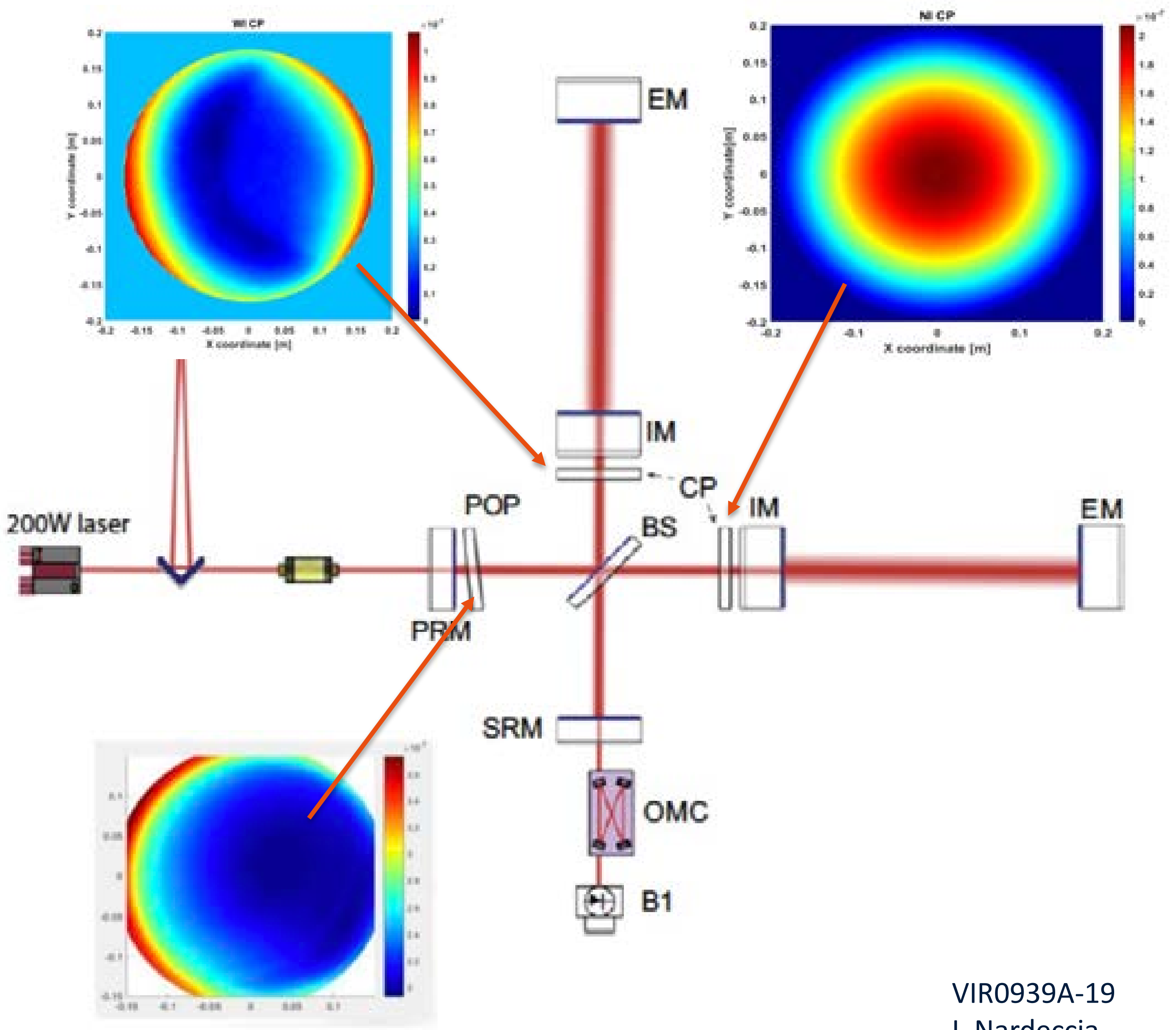


https://apps.et-gw.eu/tds/ql/?c=15418



Static Mirror Deformations

- All mirrors inside the central interferometer are polished to extremely high specifications
- Taking out the radius of curvature, some static mirror deviations from a perfectly flat surface remain
- Transmission maps of all main optics show these deviations
  - Converging or diverging
  - Non-central
  - Astigmatic



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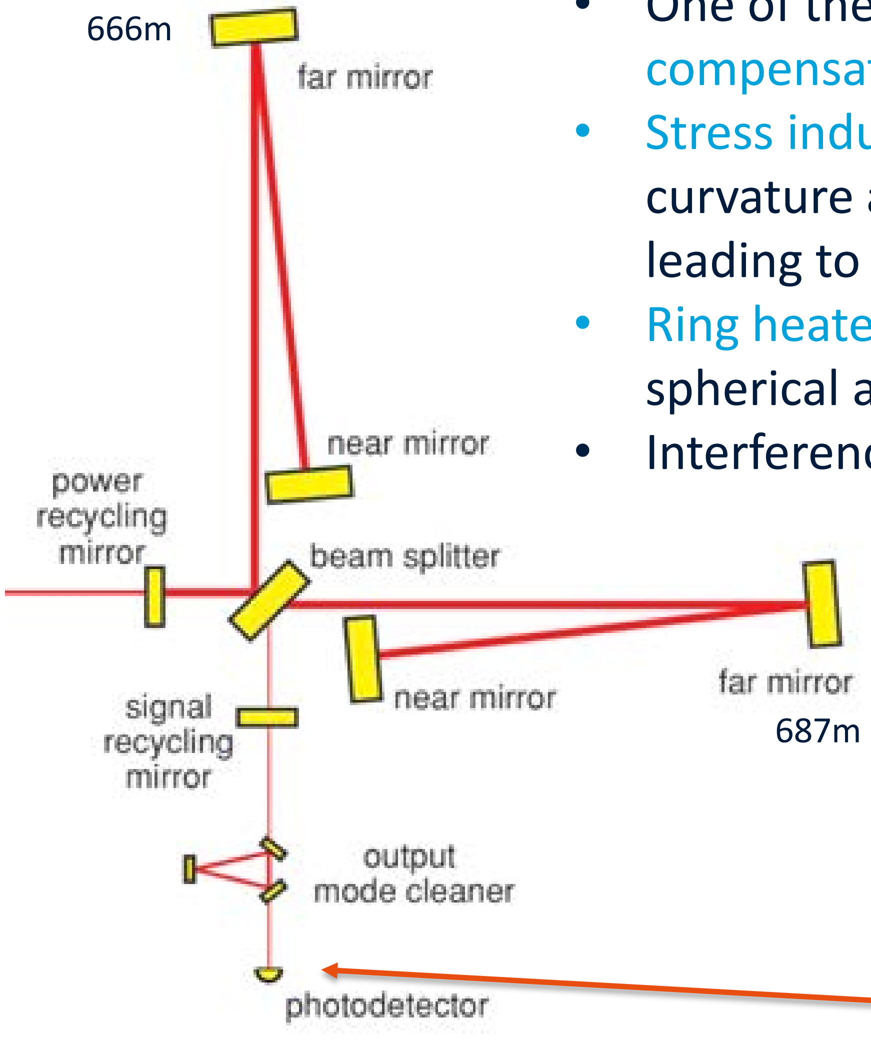
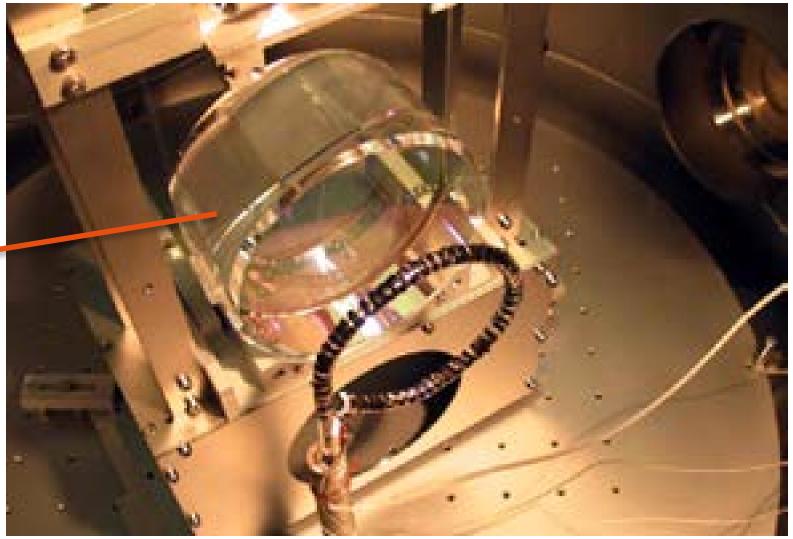
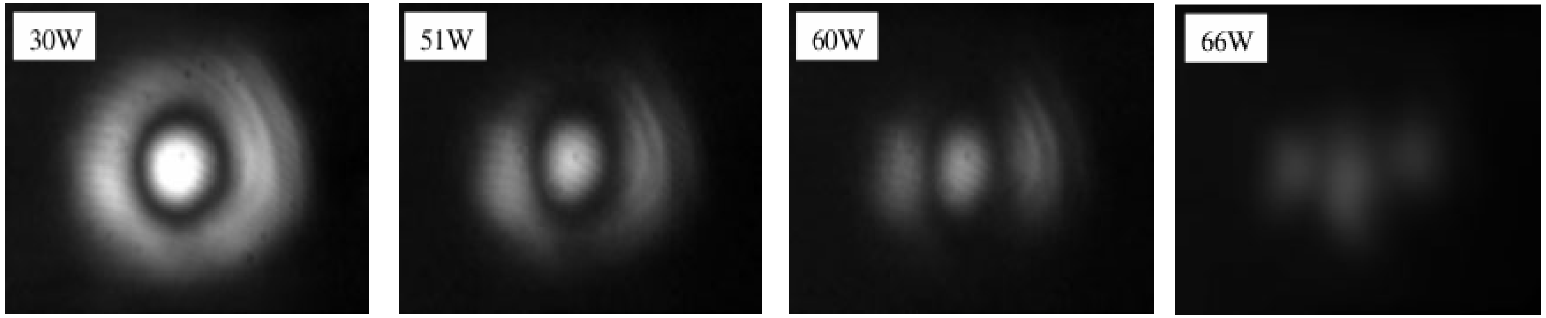
Example: GEO600



- One of the first applications of thermal compensation in GW detectors
- Stress induced by coating changed mirror radii of curvature away from design value of 640m, leading to imperfect interference
- Ring heater behind one mirror compensates spherical asymmetry
- Interference improved by factor 10

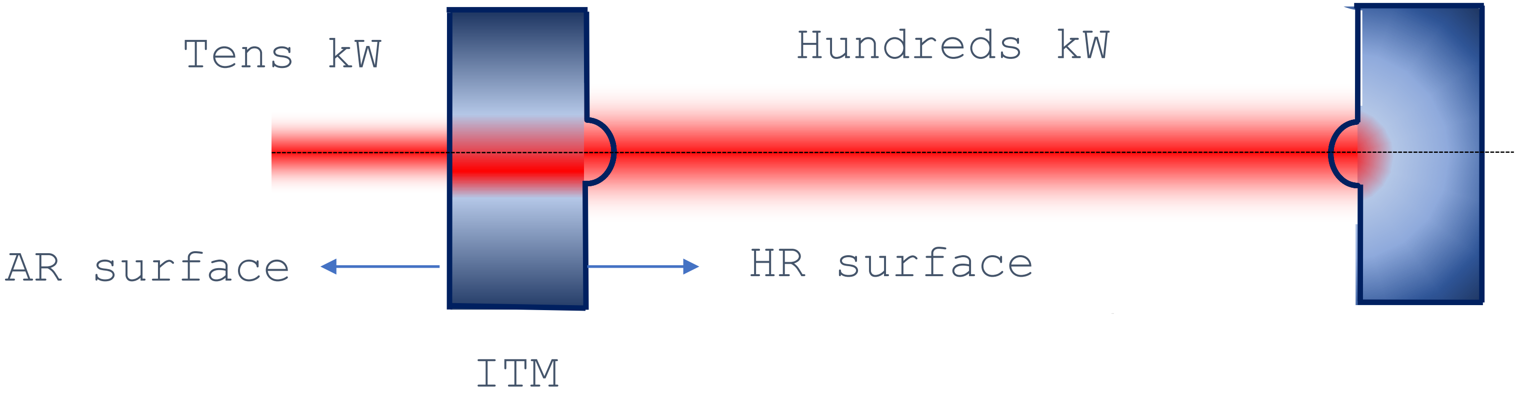


Lück et al. DOI: 10.1088/0264-9381/21/5/090, 2004



Dynamic mirror deformations

- In normal operation, several hundred kW of laser power circulate in the arms of a GW detector
- Ultra-low loss coatings (< 1ppm), still means around 100mW laser power is absorbed
- Creates temperature gradient in the mirror
- Leads to thermoelastic and thermorefractive deformation (dL/dT, dn/dT)
- Dynamic process during switching on (“locking”) of the interferometer – need dynamic actuation



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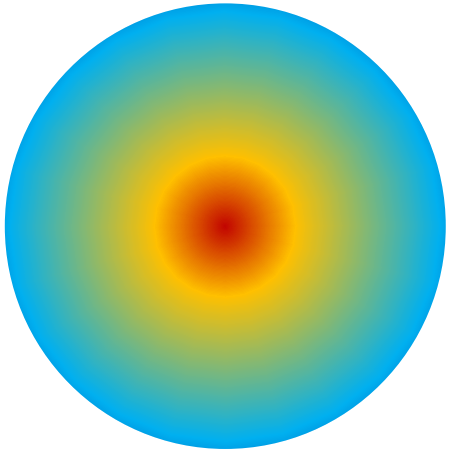
Thermal Compensation

Aspheric lens from laser heating



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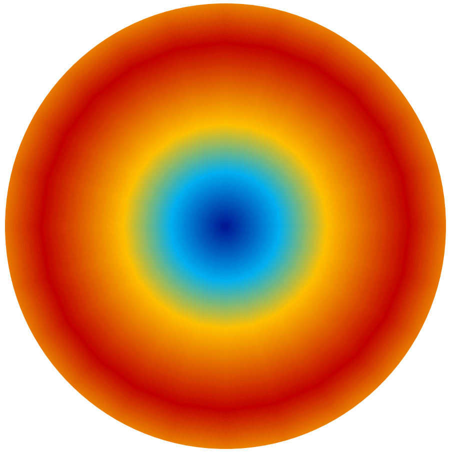
Annular heating with a CO_2 laser



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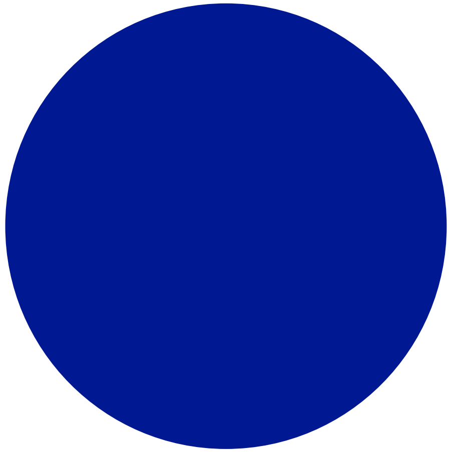
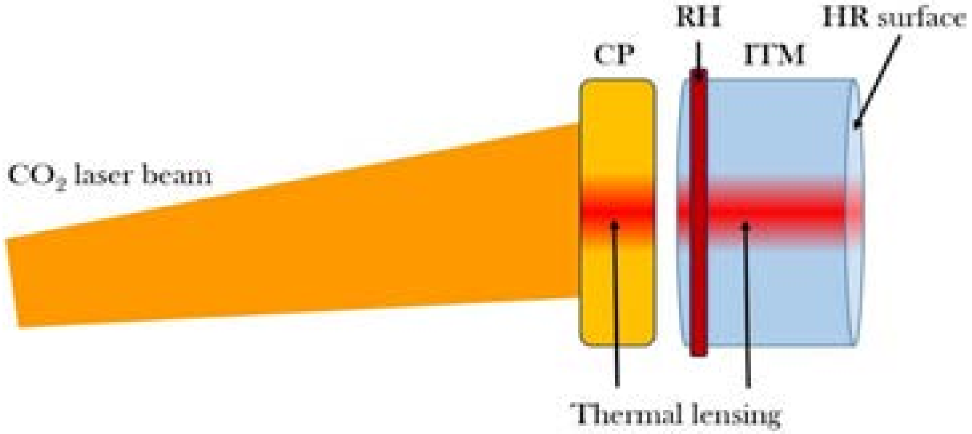
Thermal compensation of mirror deformation





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- Axi-symmetric centred pattern, to avoid thermal transient during lock/unlock of interferometer (replaces heat from main laser beam)
- Axi-symmetric annular correction, to correct thermal lensing
- Ring heater (RH) for static correction of mirror radius of curvature

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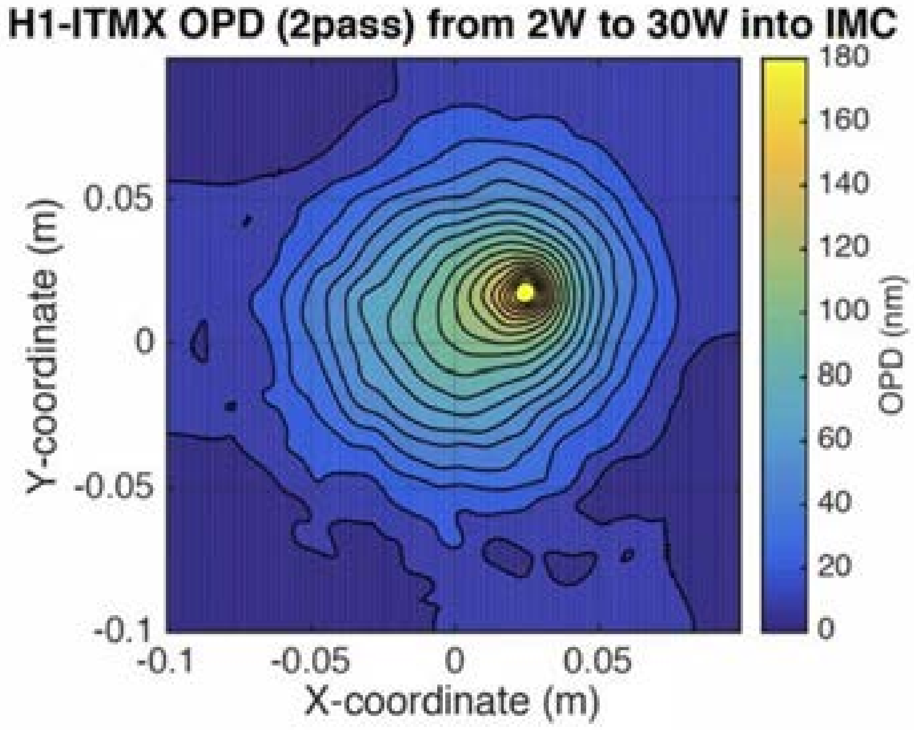
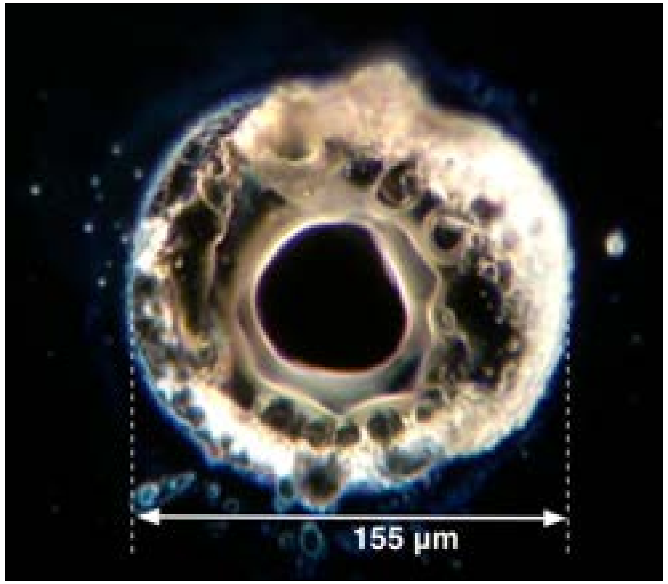
Point Absorbers

- Highly absorbing spots on the mirror surface lead to severe distortion of the surface
- Isolated phenomenon
- Investigation shows these are particles that end up buried in the dielectric coating stack
- Likely existed for a while but only now becoming a problem with increased sensitivity and laser power

- Mitigation:
  - Fine-grained thermal compensation
  - Removing the absorber (laser ablation?)
  - Preventing the creation of absorbers (??)



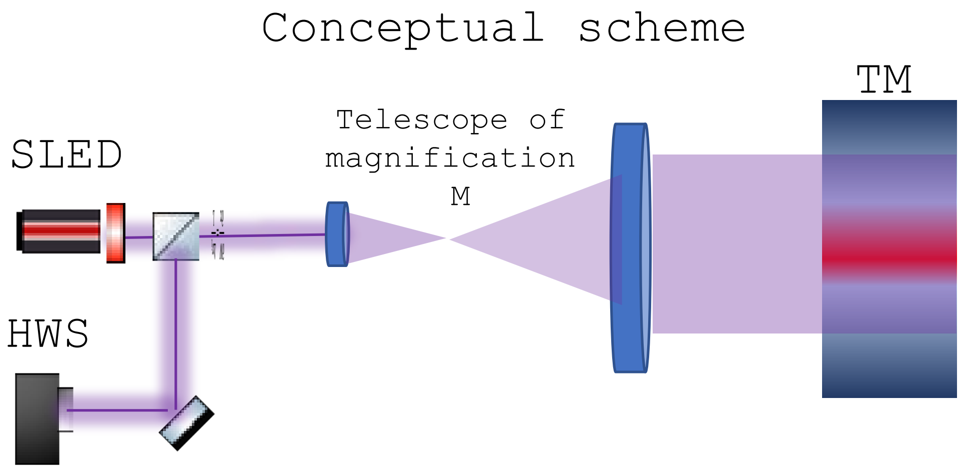


Brooks et al, https://arxiv.org/abs/2101.05828, 2021

Metrology

- Compensation, especially in a feedback loop, needs sensors that can detect deviations with sufficient SNR

- Hartmann Wavefront Sensors (HWS) measure change of wavefront reflected by mirrors relative to reference wavefront, noise level <2nm
- Indirect measurements of mirror quality through monitoring interferometer behaviour



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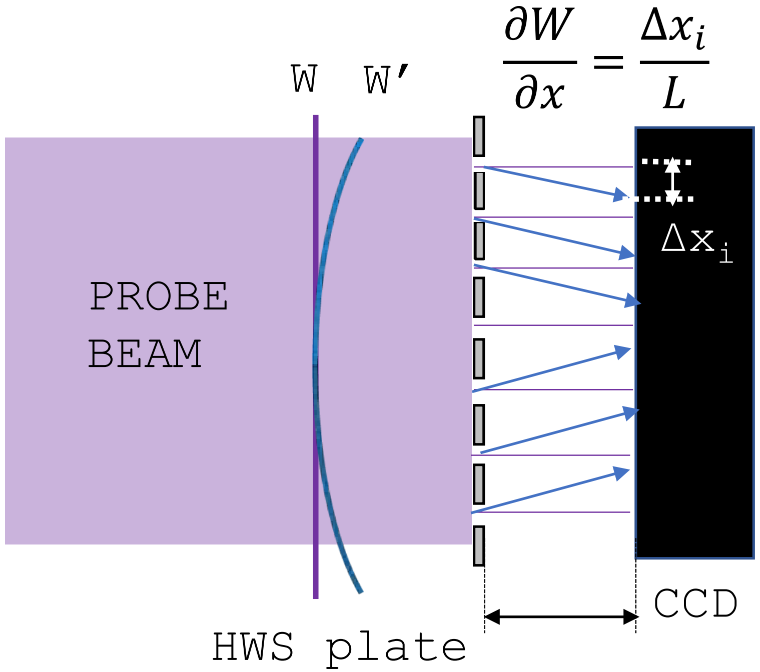
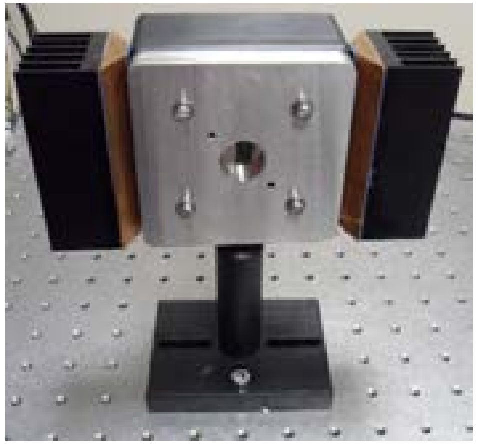


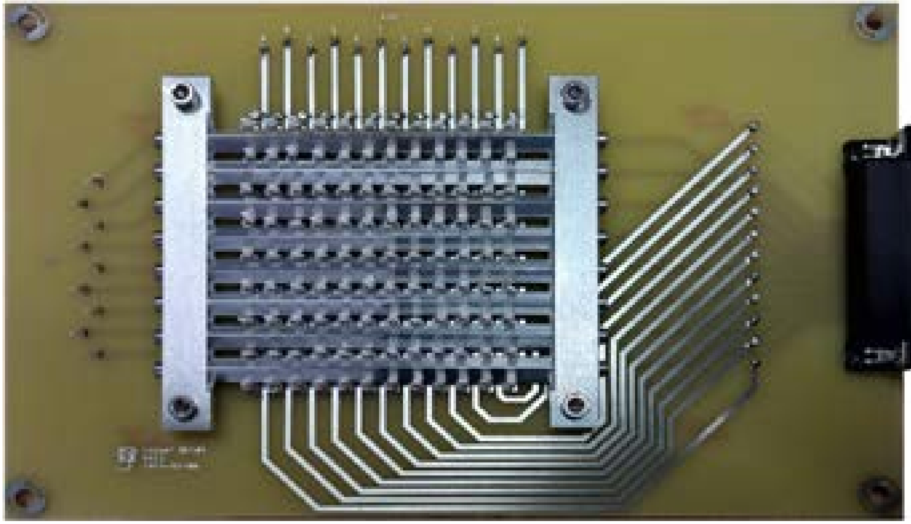


A. Brooks, PhD thesis, Adelaide 2007

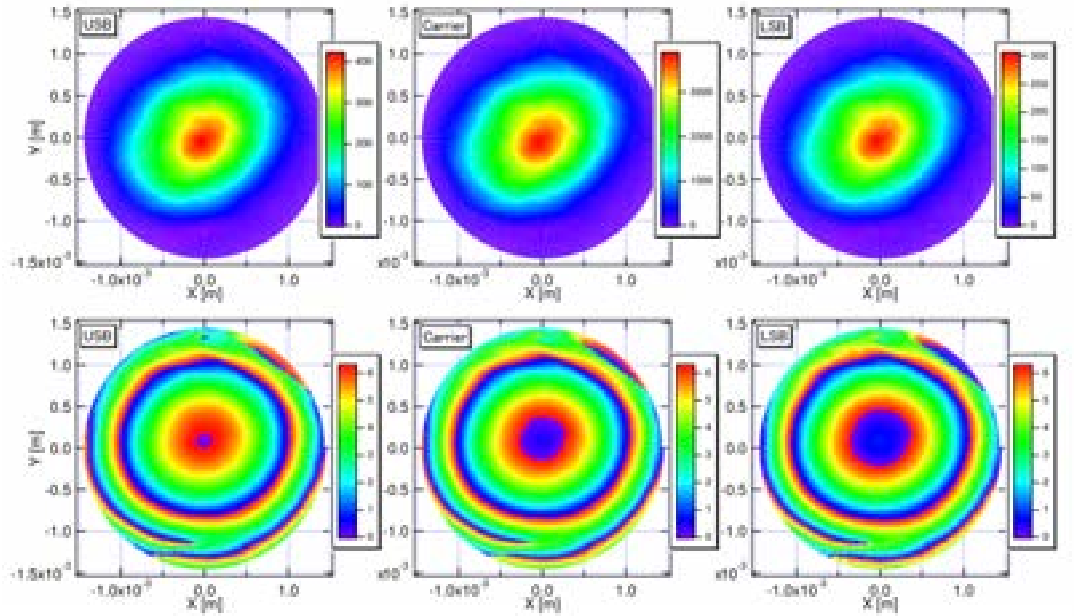
Developments in compensation techniques

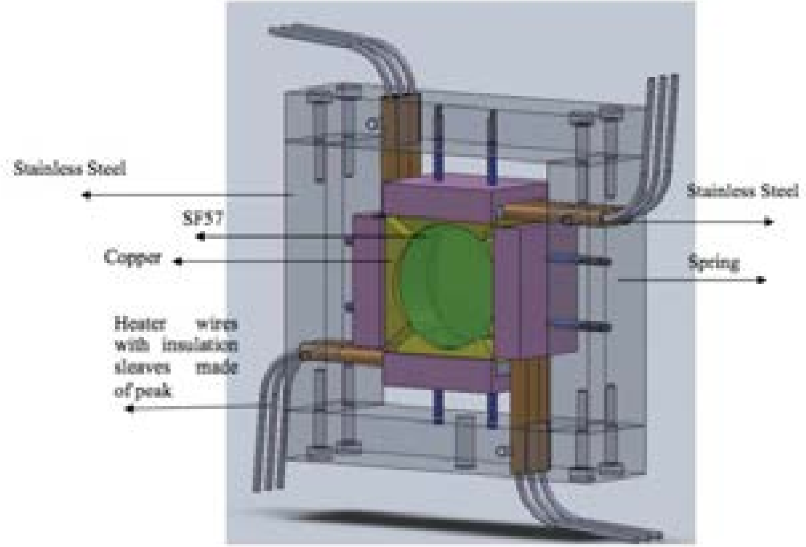
- Heater arrays to project arbitrary heating patterns on optics
- Using deformable lenses or mirrors, spatial light modulators, etc. for dynamic adaption of laser beam shape
- Phase cameras for frequency-resolved measurements of wavefronts

H. Wittel



Agatsuma et al, https://doi.org/10.1364/OE.27.018533, 2019





F. Mangana-Sandoval

The Future of GW Detectors

- Next (third) generation uses cryo-cooled silicon mirrors to reduce thermal noise, puts limits on acceptable thermal load
- High heat conductivity equates less thermal lensing, but also less actuation range; want to operate around zero-crossing of thermal expansion, further reducing actuation range
- Cryo operation
- Long baselines of interferometers mean large radii of curvature (less sagitta; absolute deviation from perfect flat is smaller) – need better metrology
- Correction of secondary mirror deformations becoming more important with increased sensitivity
- Strong activity and collaboration with industry and research partners in NL/BE/D – get in touch!

ETpathfinder
www.etpathfinder.eu

etest-emr.eu

et2smes.eu

Einstein Telescope
www.et-gw.eu