ADONI 2016-
Florence 14-16 April

ADAPTIVE OPTICAL SYSTEM FOR ADVANCED GRAVITATIONAL WAVES INTERFEROMETRIC DETECTORS

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INFN Roma Tor Vergata-
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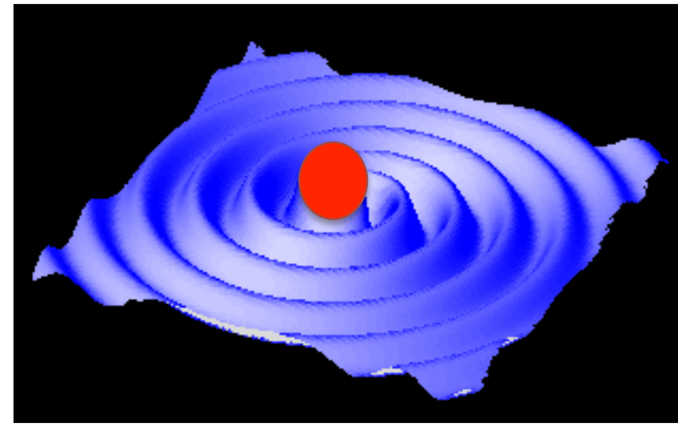
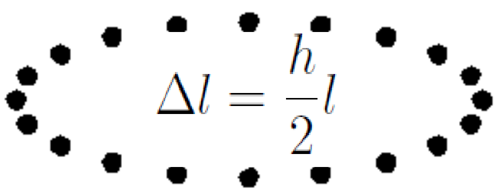
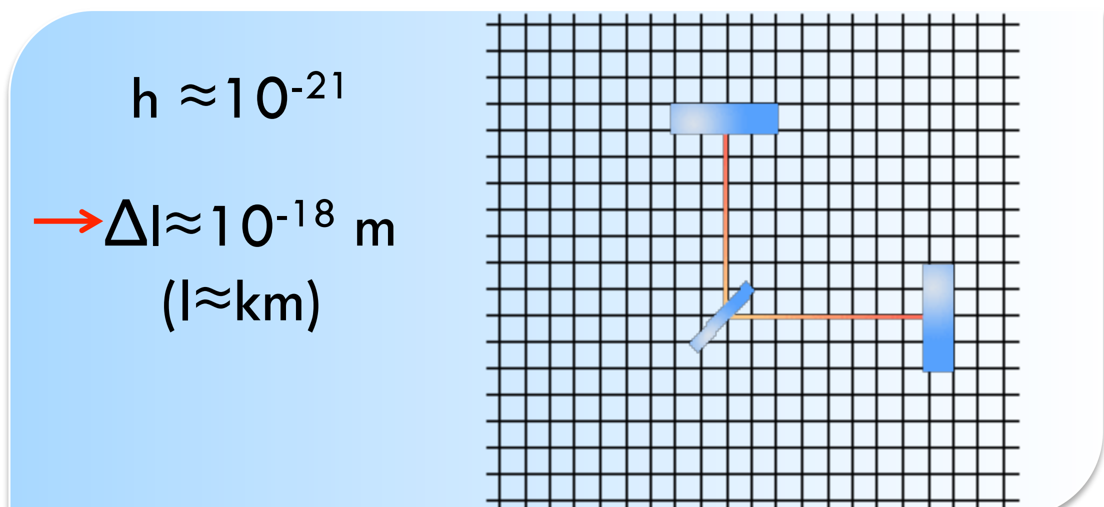
Gravitational waves

- ✓ Predicted by General Relativity (1915);
- ✓ perturbations of the space metric that propagate at speed of light;
- ✓ generated by massive bodies moving with accelerated quadrupole moment;
- ✓ induce a quadrupolar deformation on the space-time geometry changing the distance among free-falling bodies.





$$\Delta l = \frac{h}{2} l$$



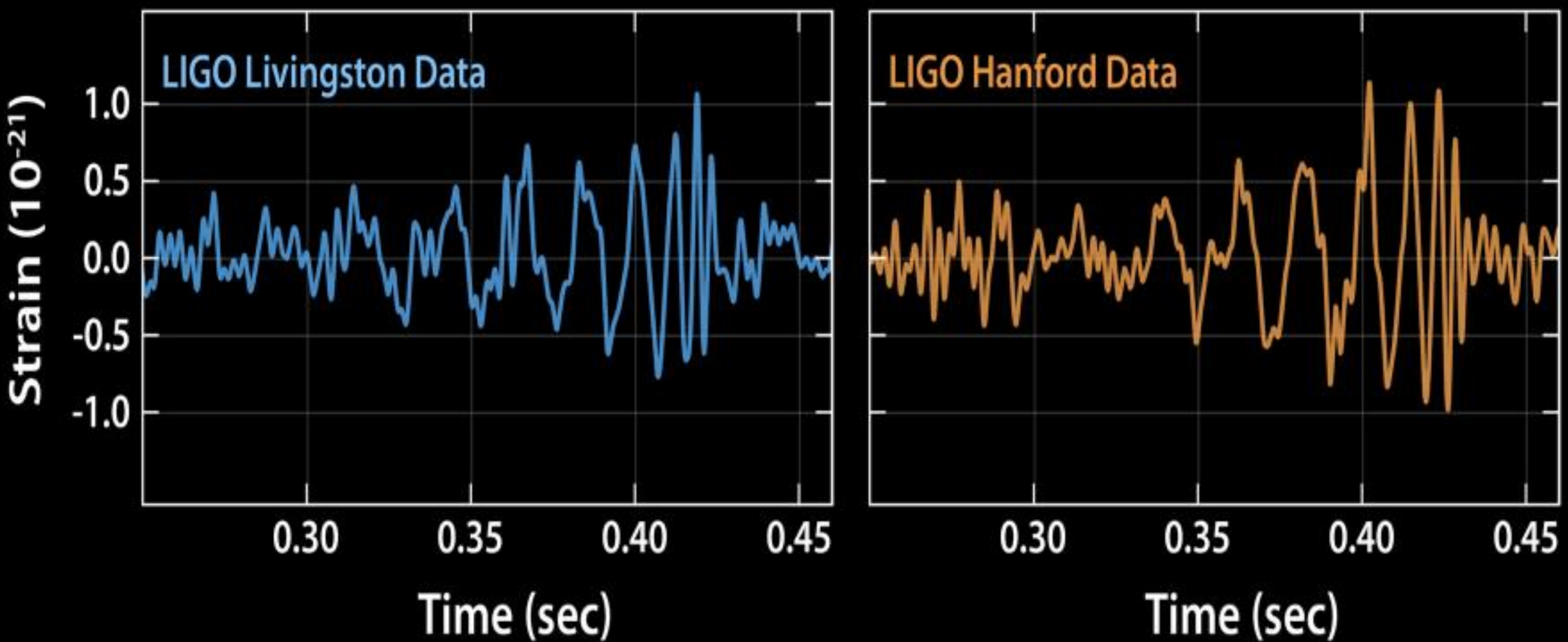
The discovery of gravitational waves

Coalescence of Binary black holes system

$M_{BH1} = 36\ M_{sol}$ $M_{FBH} = 62\ M_{sol}$ $D_{BH\text{-}BH\ (before\ merger)} = 250$ km

$v_{BH\ (before\ merger)} = c/2$

$M_{BH2} = 29\ M_{sol}$ $E_{gw} = 3\ M_{sol}$ Distance = 410 Mpc



PRL 116, 061102 (2016)

LIGO & Virgo Interferometers

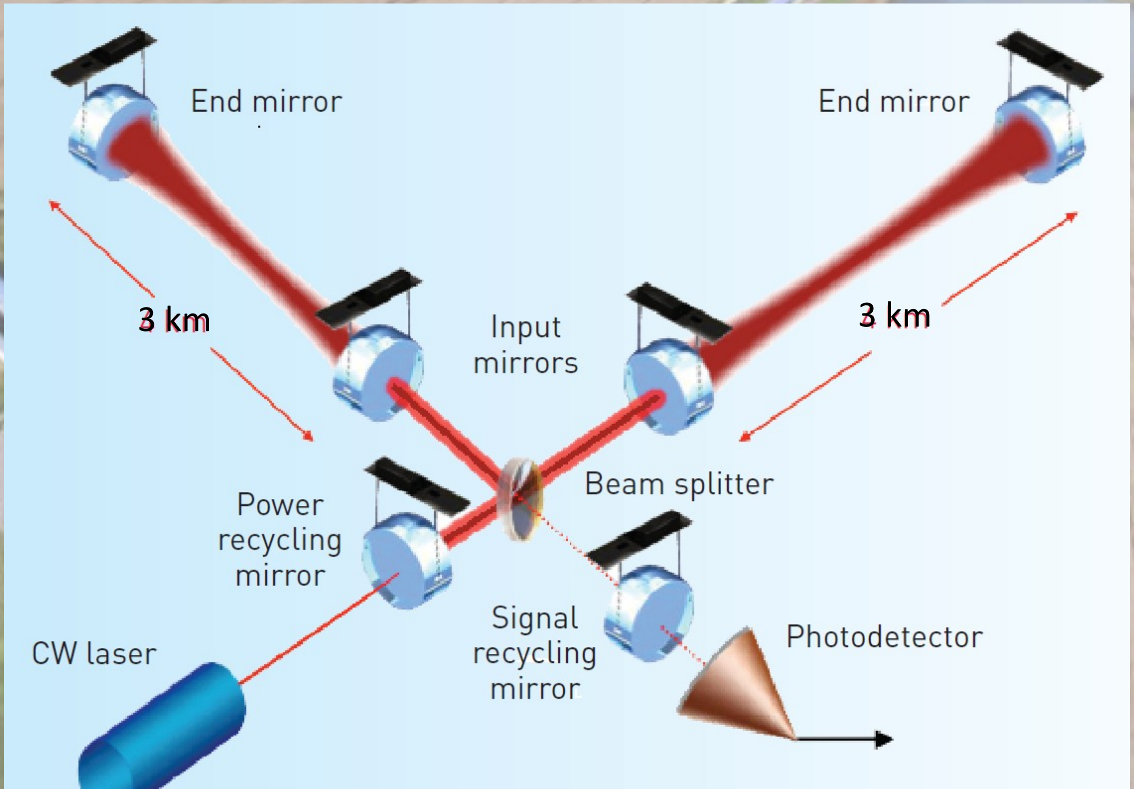
Detection range: 10 Hz-10 kHz

Coalescing NS-NS (1.4 $M_\odot$) → 150 Mpc

Coalescing BH-BH (M=40 $M_\odot$) → 1 Gpc

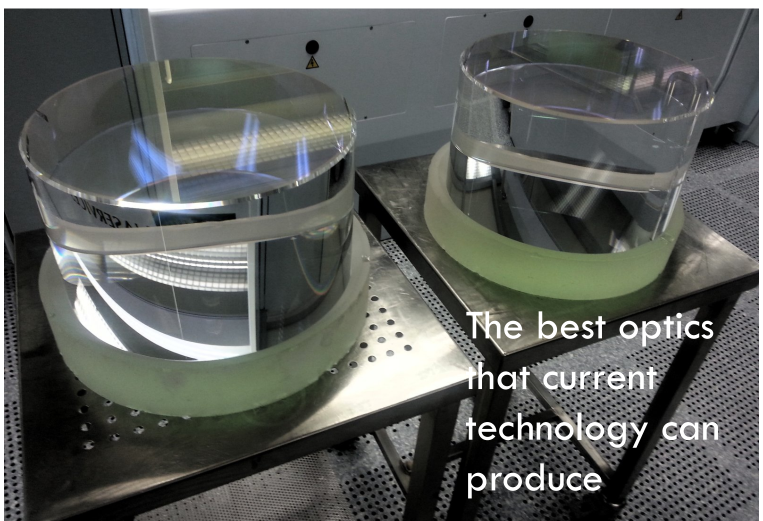
ADVANCED VIRGO

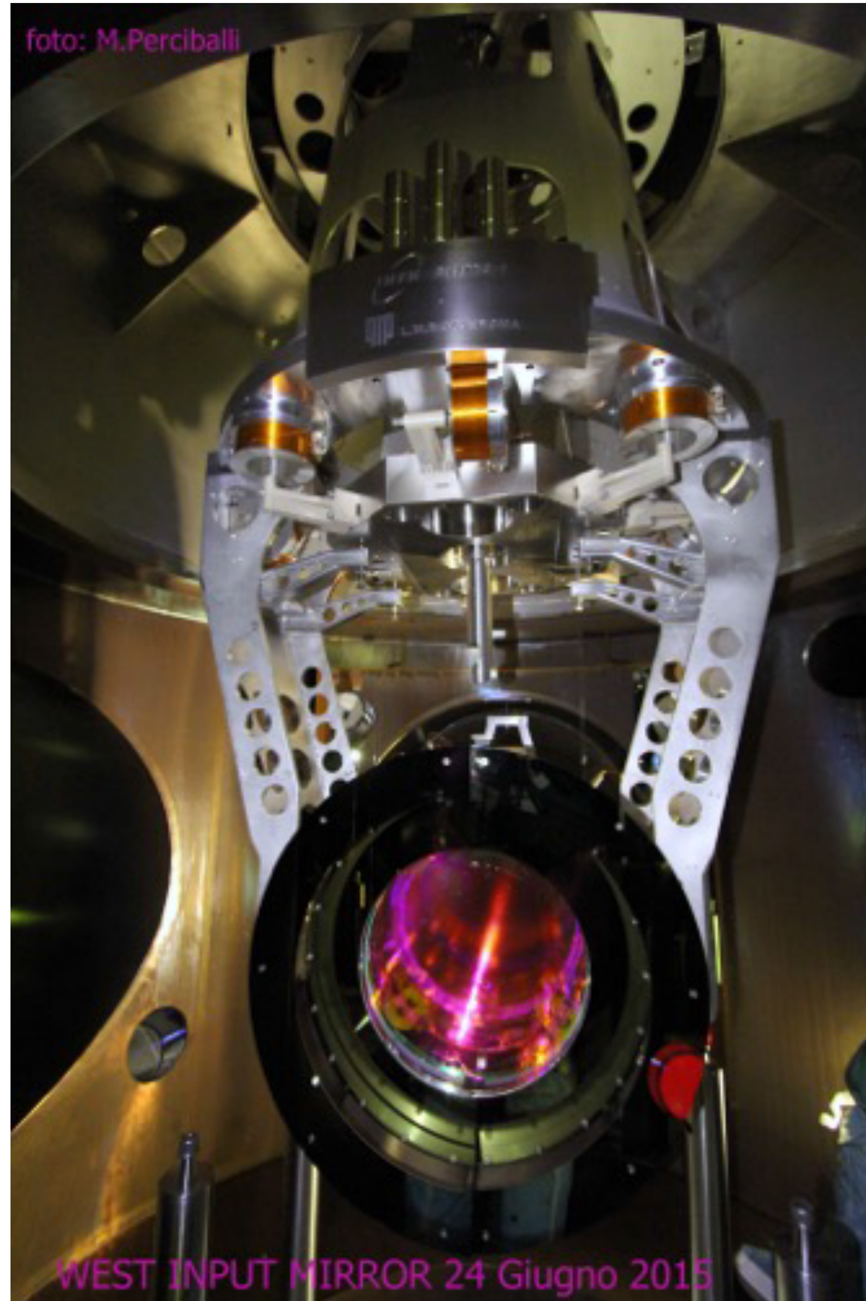
- ✓ Michelson Interferometer (dark fringe operation)
- ✓ Fabry-Pérot optical cavities
- ✓ Power Recycling cavity
- ✓ Signal Recycling cavity
- ✓ Gaussian Mode TEM_{00}



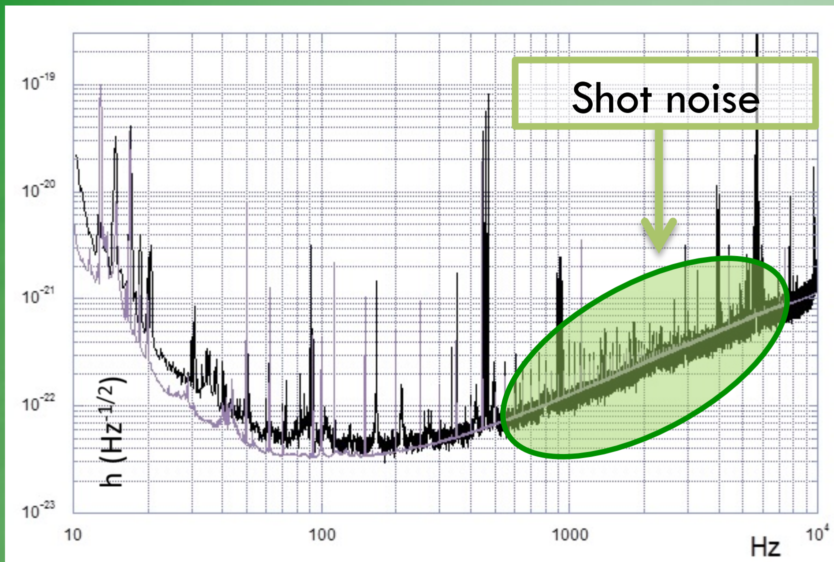
Spherical Mirrors RoC≈1.5 km

- ✓ Fused silica substrate (diameter=35 cm, 40 kg)
- ✓ Amorphous multi layer coating made by LMA (Lyon) (absorption: 0.2 ppm)
- ✓ Reflectivity: 99.99%
- ✓ Fused silica fibers to suspend the mirror (monolithic)

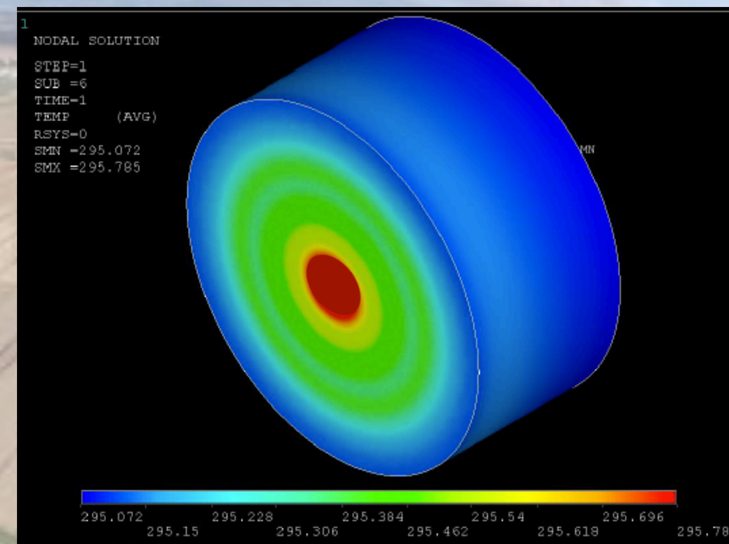




Kill the shot noise



Thermal Gradient inside Optics

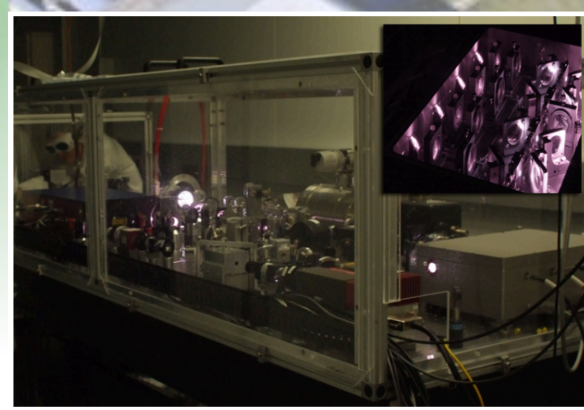


Shot noise

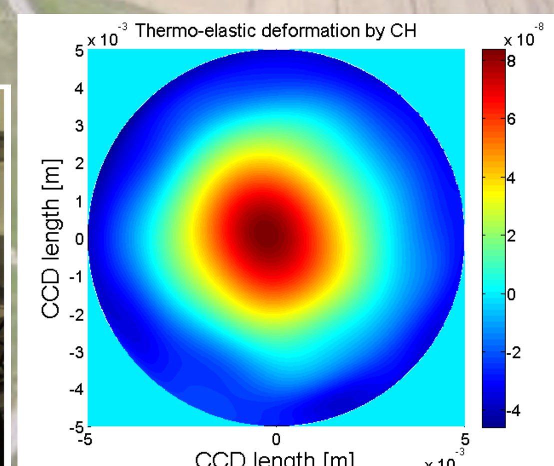
- ✓ Ultra stable YAG @1064 nm laser P_{in}=200 W

$$h_{shot} \propto \frac{1}{\sqrt{P_{in}}}$$

- ✓ Power circulating in the Fabry-Pérot cavity P=700 kW (Coating Absorption ≈ 200 mW)



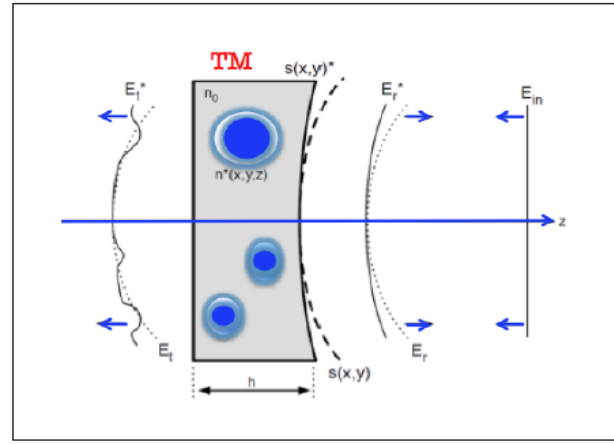
Wavefront Aberrations



Wavefront aberrations: sources/effects/solution

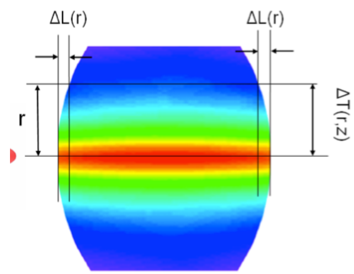
Sources

- ✓ imperfections in the production of the material used for the mirrors (cold defects);
- ✓ absorption of optical power in the coatings and substrates of the optics (dynamic effects).

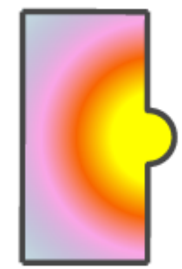


Thermal effects

- ✓ Thermal lensing



- ✓ Thermo-elastic effect

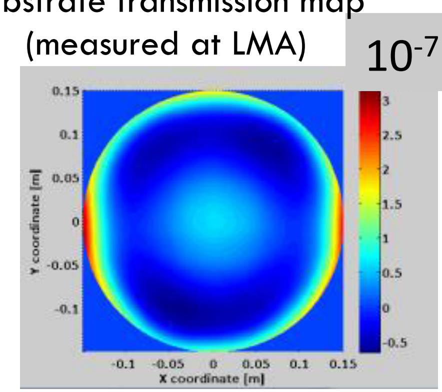


Consequences

Scatter light to Higher Order Modes (HOM):

- ✓ Error signals power to control the cavities decreases;
- ✓ Fabry-Pérot Cavity power decreases ->loss of sensitivity;
- ✓ Worsen interference at Beam Splitter -> junk light at the dark port.

Substrate transmission map (measured at LMA)



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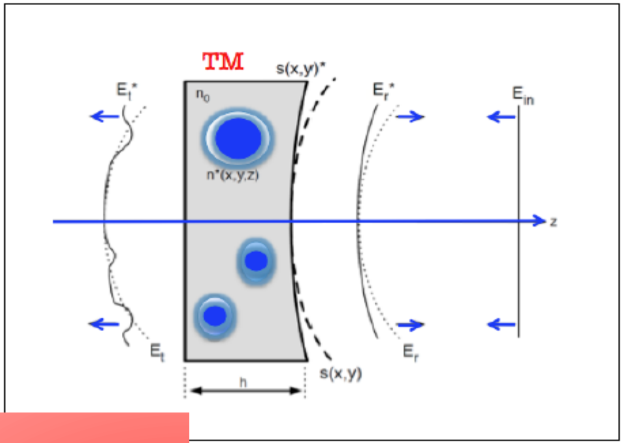
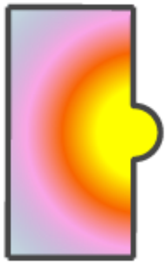


Thermal effects

- ✓ Thermal lensing

THERMAL COMPENSATION SYSTEM

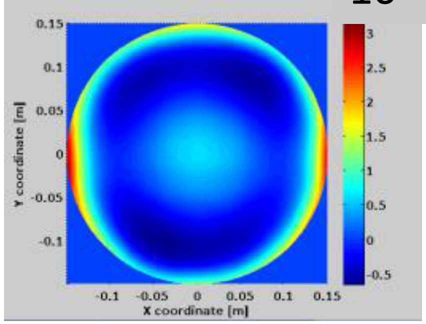
astic effect



Consequences

Substrate transmission map (measured at LMA)

10^{-7}



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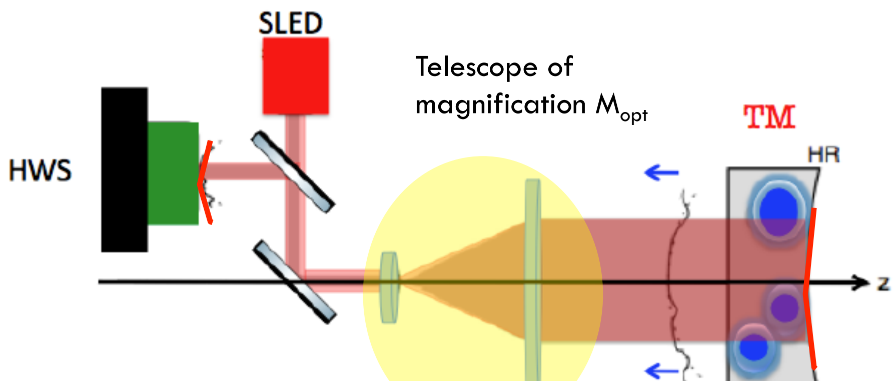
Thermal Compensation System guidelines

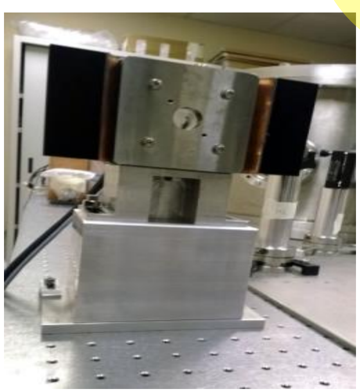
- ✓ The strategy is to induce in the optics an aberration equal but opposite to the thermal effect;
- ✓ the level of power absorption inside the optics is time dependent;
- ✓ mirrors are suspended (in free-falling condition), they cannot be touched;
- ✓ the only "touchless" way to heat the mirror is by shining it with a radiation;
- ✓ Wavefront aberration must be compensated with a precision better than 2nm RMS;
- ✓ Radius of curvature of mirrors must be controlled within +/- 2m
- ✓ An adaptive optical system to follow the thermal state of the interferometer is needed:
  - **Sensors** must be able to measure the wavefront distorsion with the required precision;
  - **Actuators** must be able to change the strength and the shape of the correction in "touchless" way.

SENSOR: Hartmann wavefront sensor (HWS)

- ✓ It measures the change of a 'live' wavefront relative to a reference wavefront through an uncoherent probe beam [fiber coupled superluminiscent diode (SLED)];

- ✓ AdV requirement RMS <2nm satisfied;





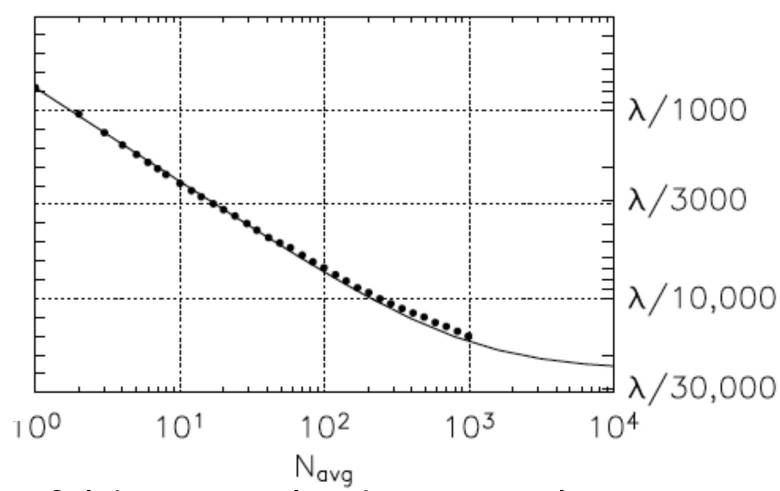
Shot to shot $\lambda/1450$;
Improved with averaging $\lambda/15500$;
Accuracy $\lambda/6800$ @820 nm

A. Brooks '*Hartmann Wavefront Sensors for Advanced Gravitational Wave Interferometers*' (PhD thesis, University of Adelaide, 2007)

- ✓ ad-hoc telescope to demagnify ($M_{opt}=f_2/f_1<1$) the probe beam size from the mirror surface to the sensor;
- ✓ location in the image plane of the aberrated surface:

$$R_{TM} = M_{opt}^{\ 2} R_{HWS}$$

HWS sensitivity

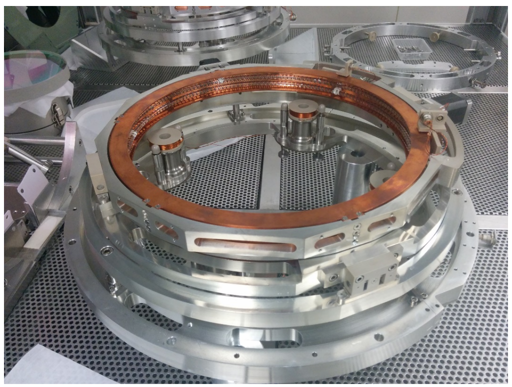


Solid curve: simulated assuming only random, stationary noise in the spot centroids
Dotted curve: measurements

Actuators.1

Compensation of Thermo-elastic effect

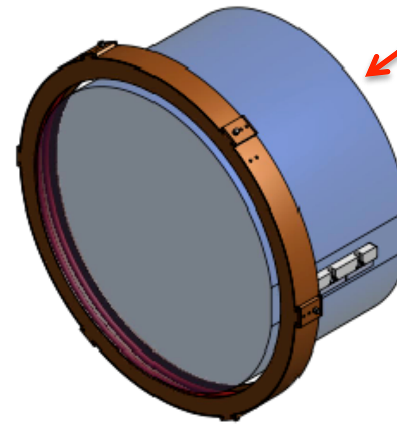
1. **Ring Heater (RH):** corrects errors in the radius of curvature of mirrors due to the absorption of the laser power and manifacturing accuracy.



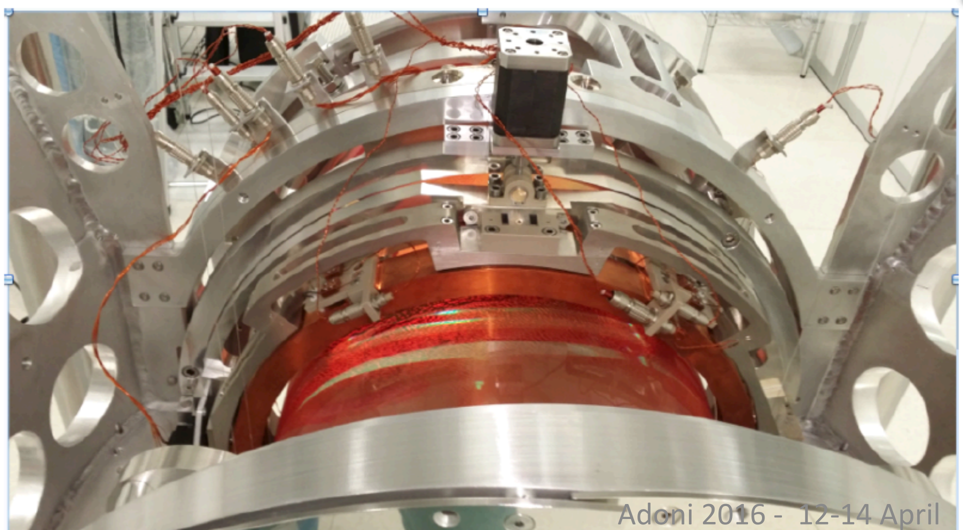
Silica rings with NiCr wires as conductors.

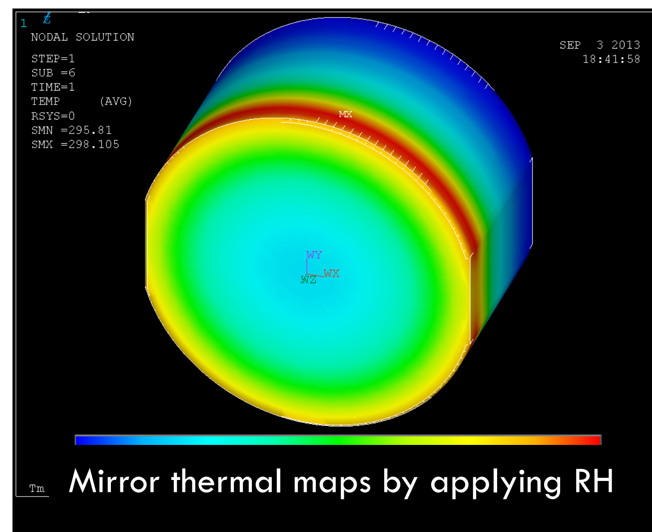
Copper shield to increase the efficiency

Mirror surface in the Fabry-Pérot cavity



FEA Simulation



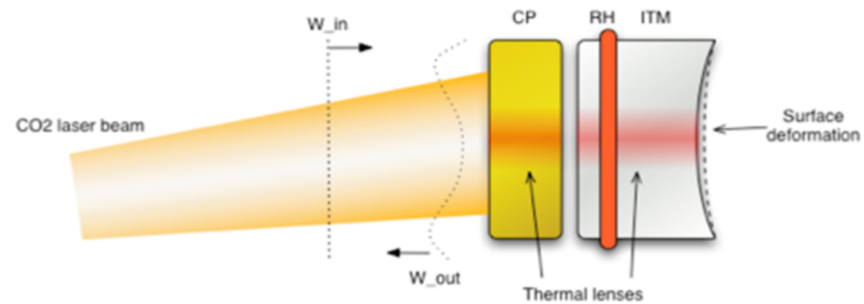


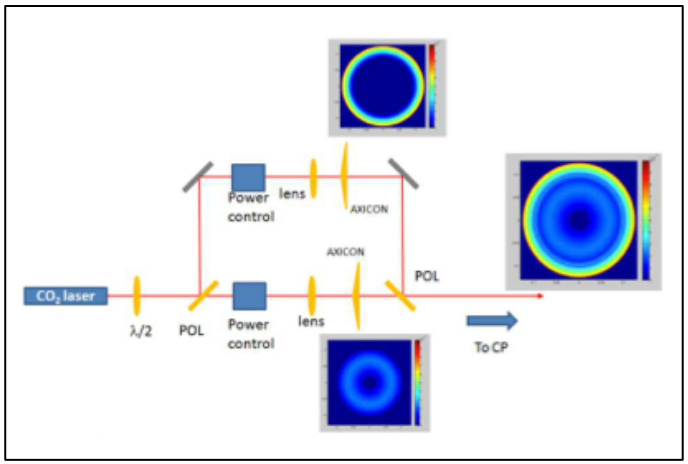
Mirror thermal maps by applying RH

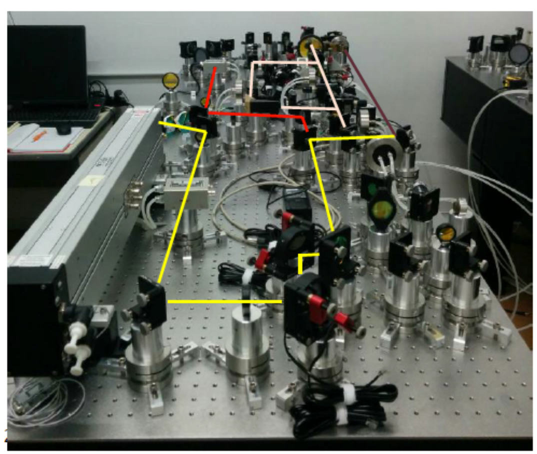
Actuators.2

Compensation of Thermal-lensing effect

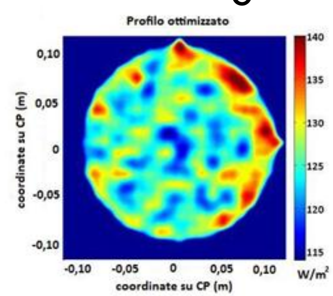
2. Double axicon system (DAS): two CO_2 annular beams incident on auxiliary optic called compensation plate (CP) to correct the axial-simmetry terms of thermal lensing.





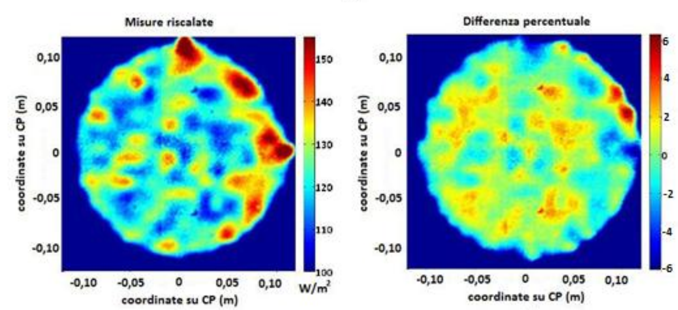


3. Scanning system: a modulated CO_2 beam scanning the CP surface to correct the nonsymmetric terms of thermal lensing.



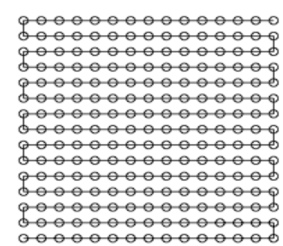
(a)

Scan grid and beam parameters		
area	A_{scan}	24 cm x 24 cm
number of points	N	25x25
Distance among close points	d	1 cm
Grid shape		raster scan
Gaussian width	σ	8.45 mm

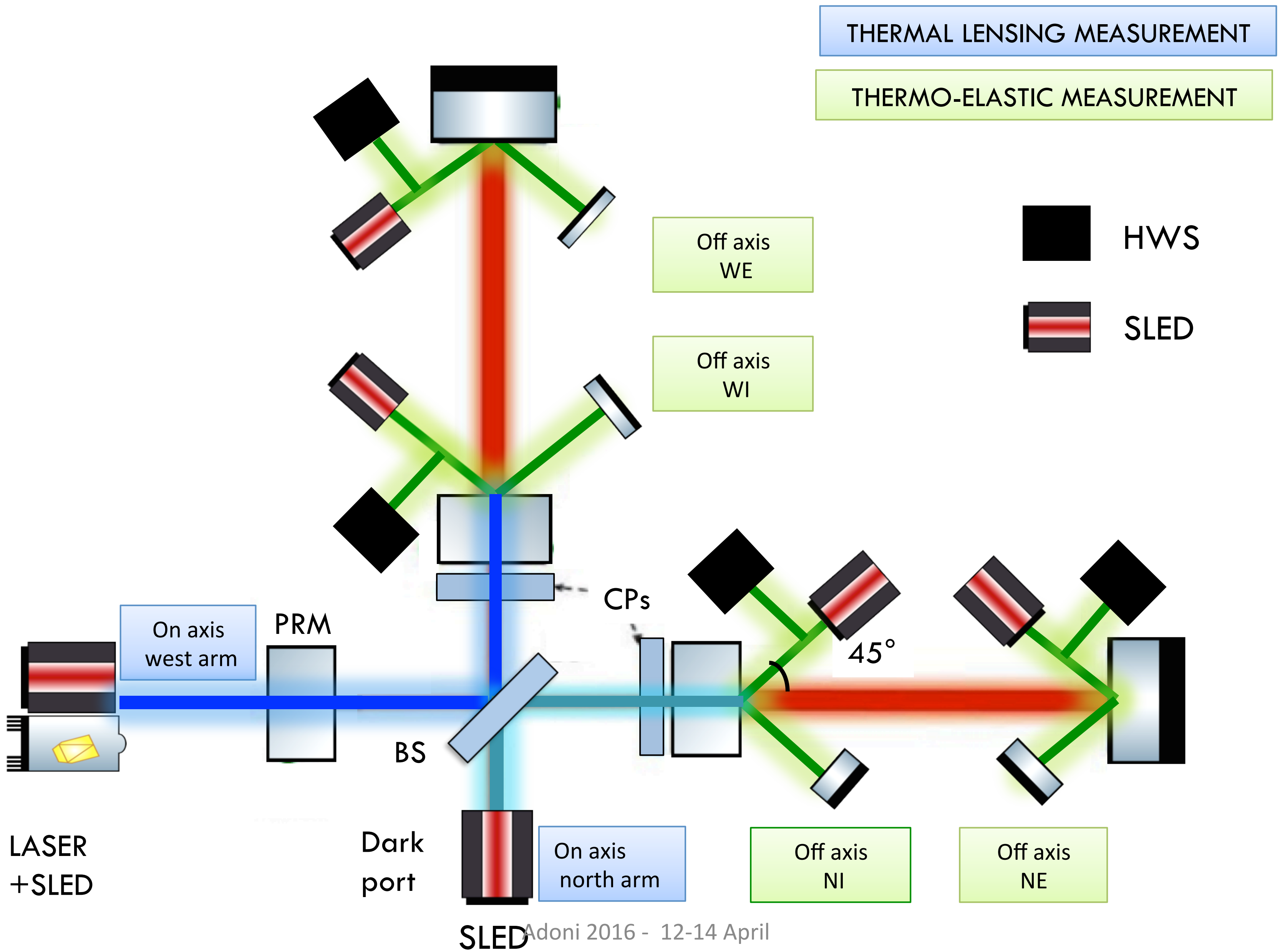


(b) (c)

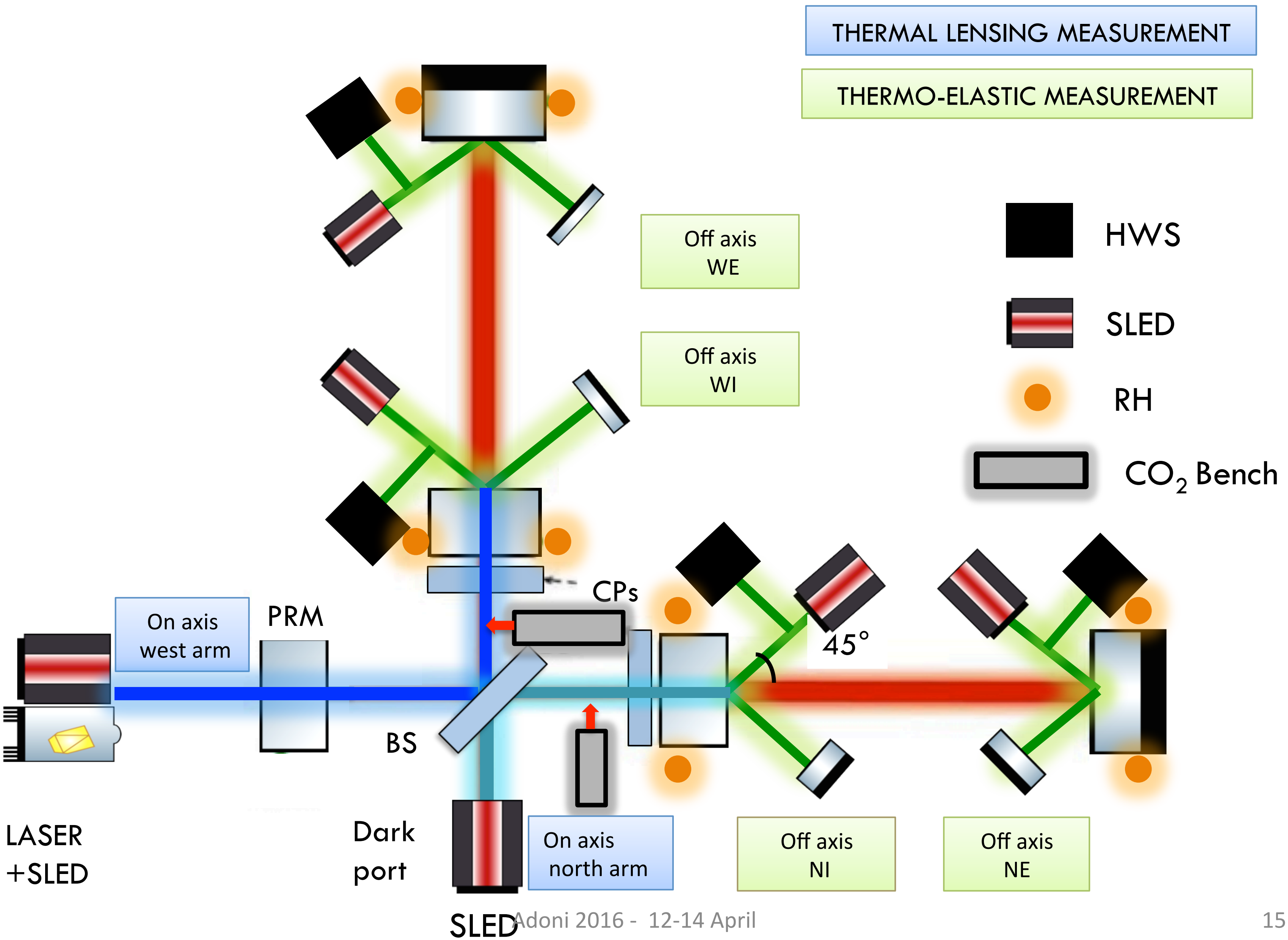
Scanning Pattern



Sensors in AdV

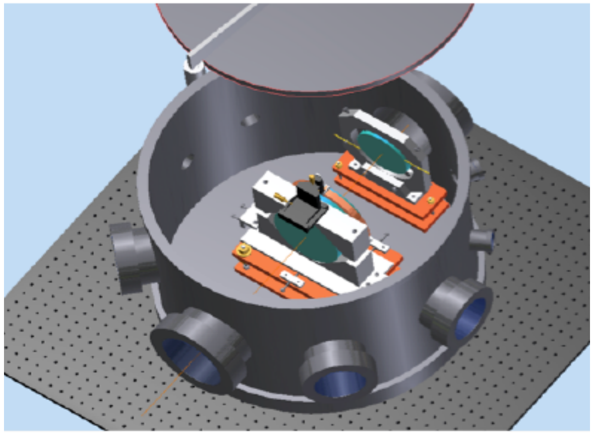


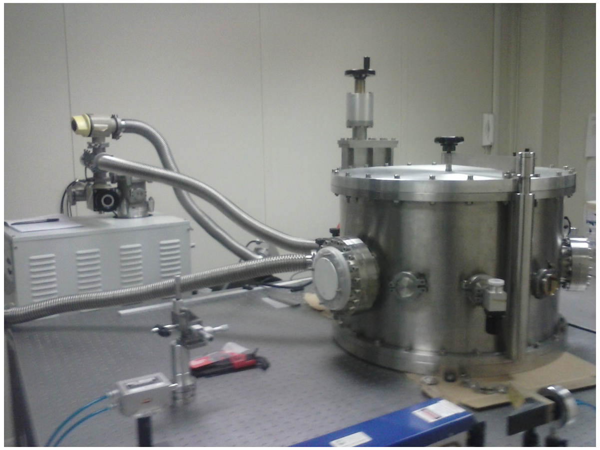
Sensors and Actuators in AdV



TeTis (Testing the effect of TCS integrated strategies)

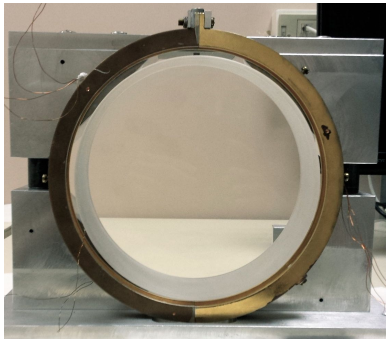
- ✓ Scaled-down version of AdV TCS;
- ✓ Extremely sensitive system to investigate both the thermal effects and the performances of sensors and actuators.

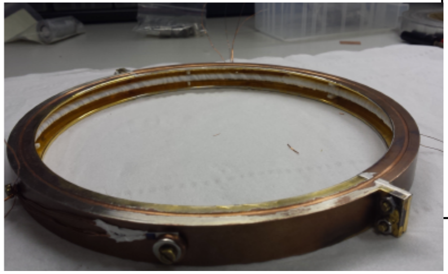


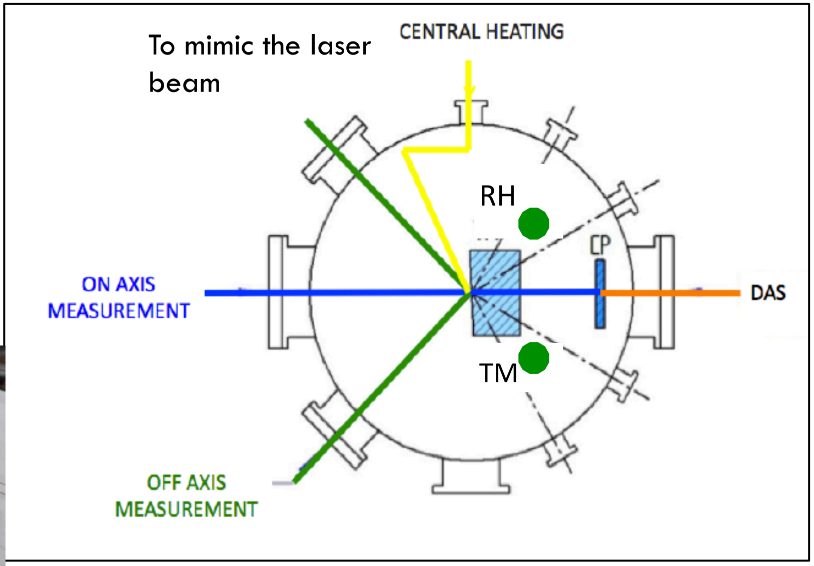


Test Mass	
Material	SiO_2
Wedge	$3°$
Thickness	$[87 \div 94] mm$
Diameter	150 mm
RoC	∞

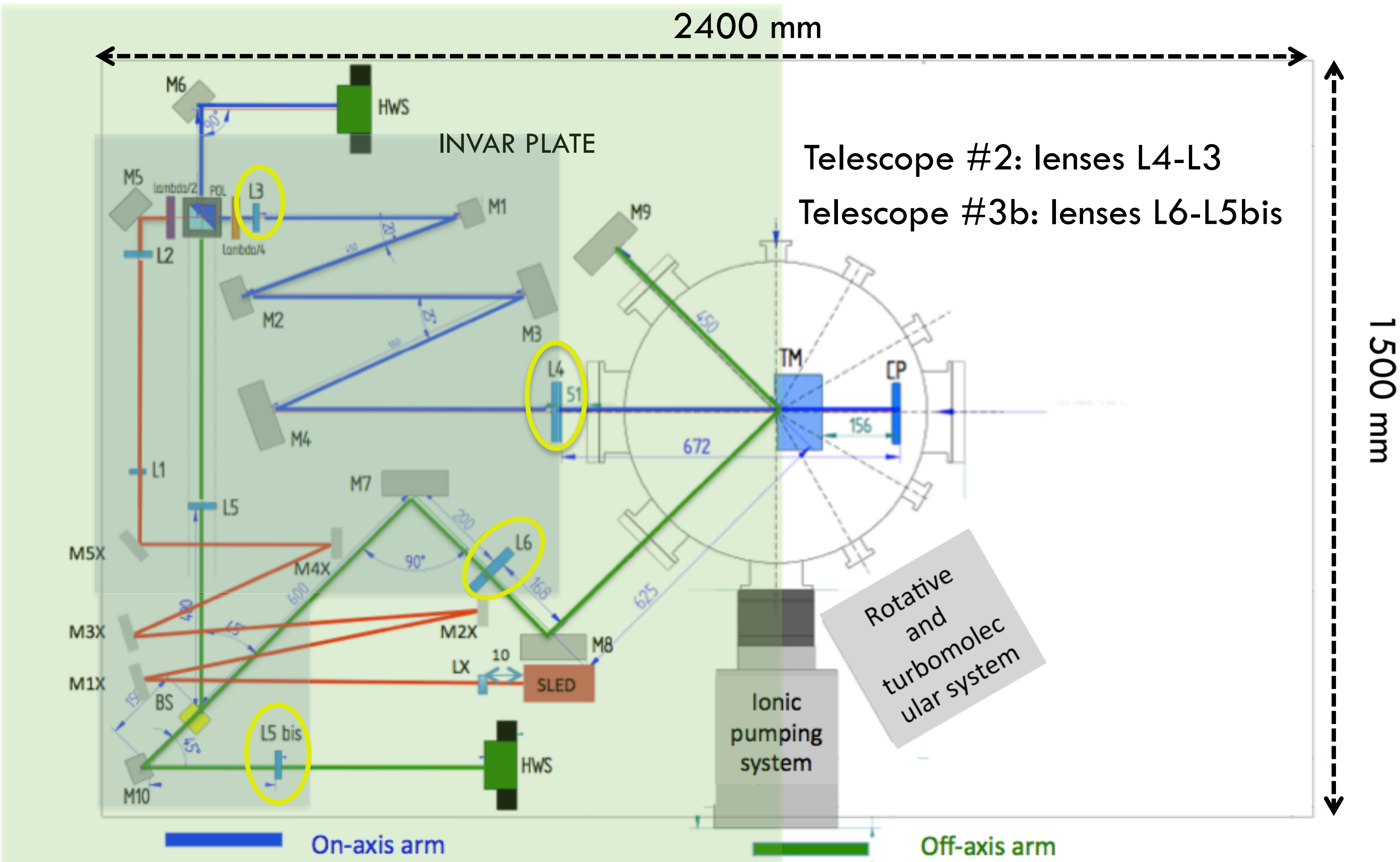
Compensation Plate	
Material	SiO_2
Wedge	//
Thickness	$15\ mm$
Diameter	$120\ mm$



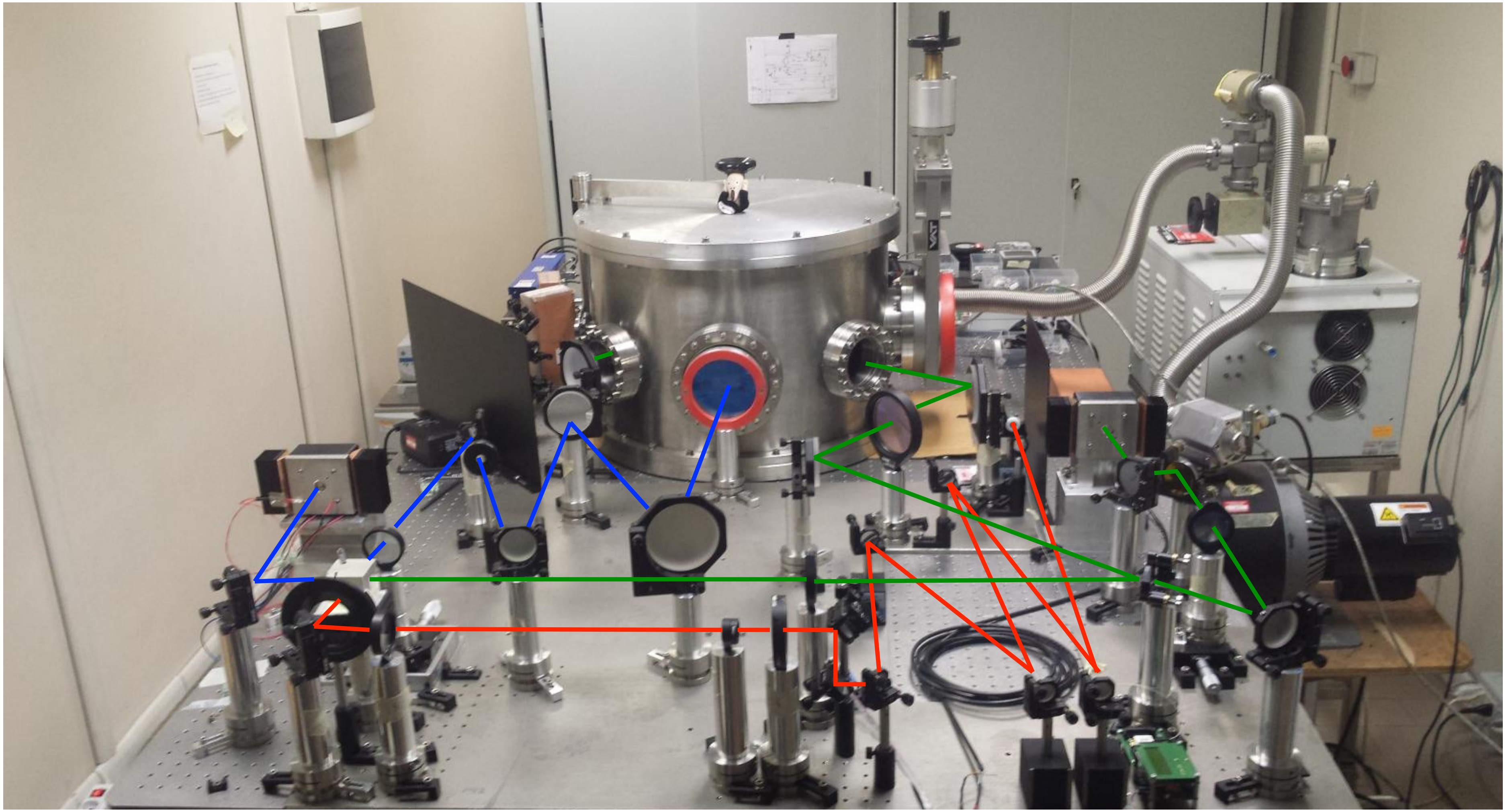




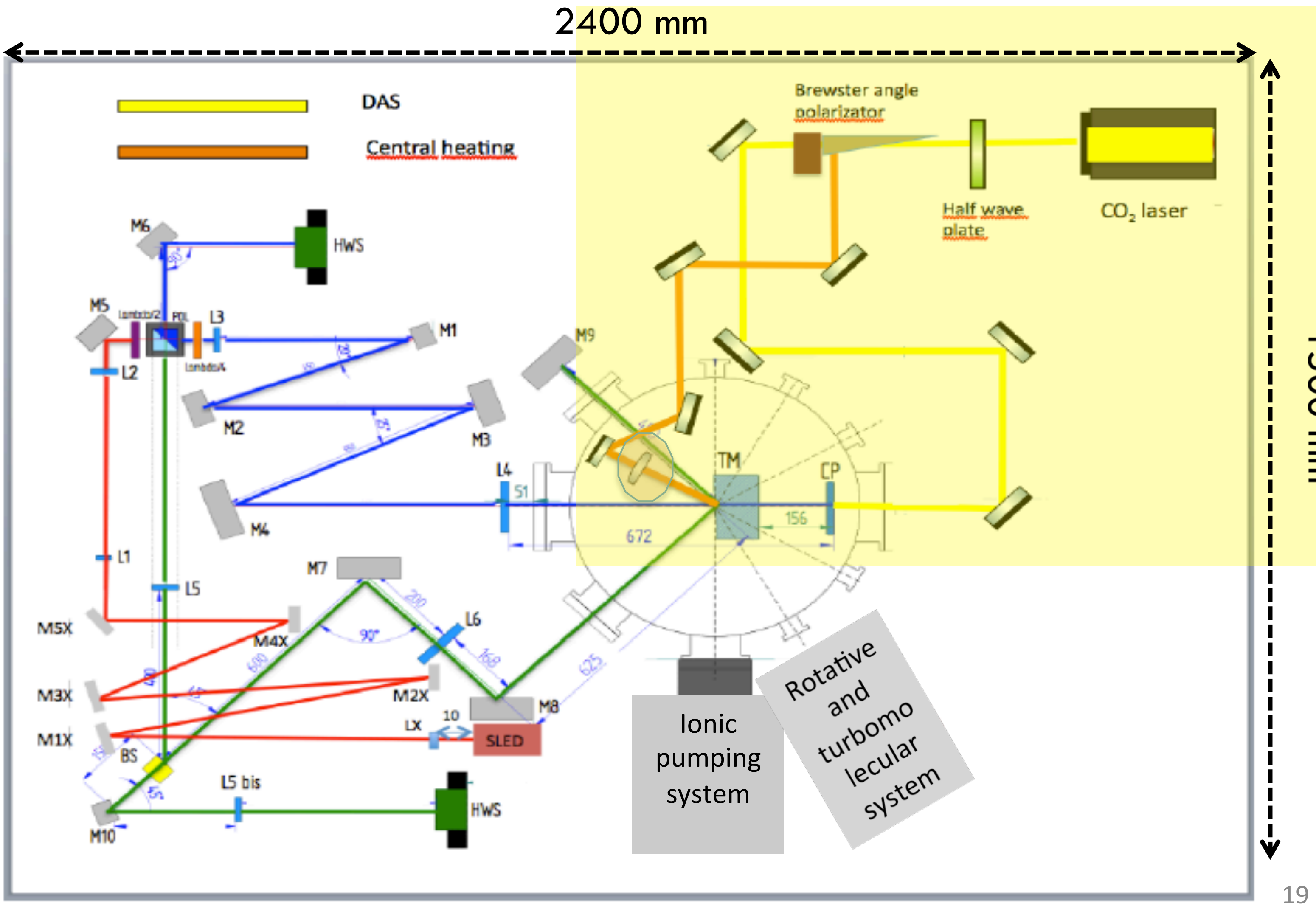
Sensing optical layout



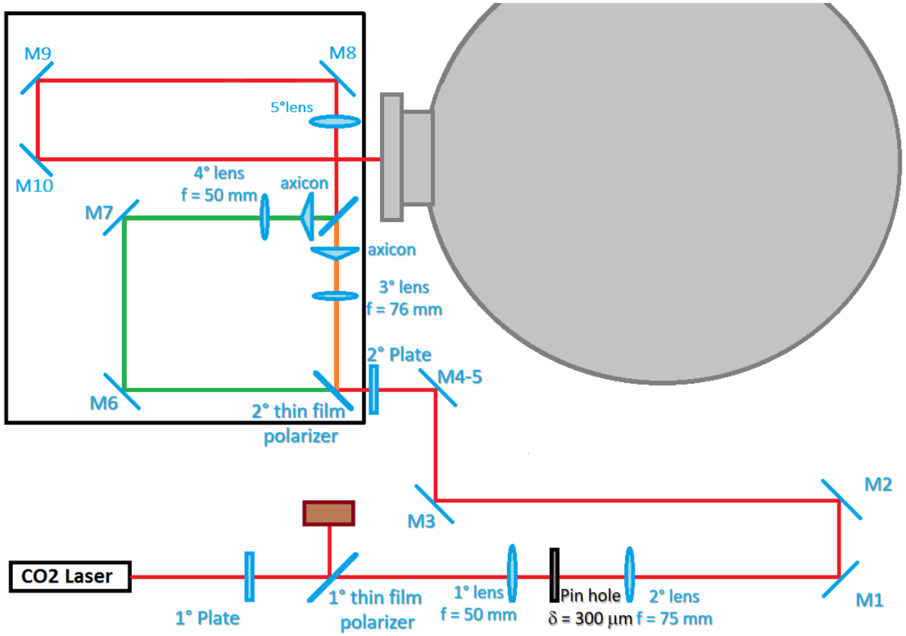
Sensing



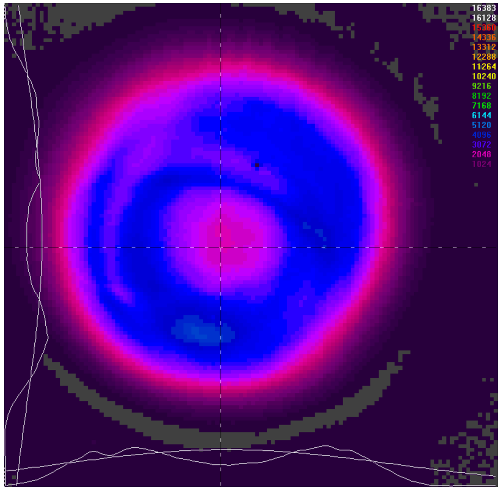
Central heating/DAS optical layout



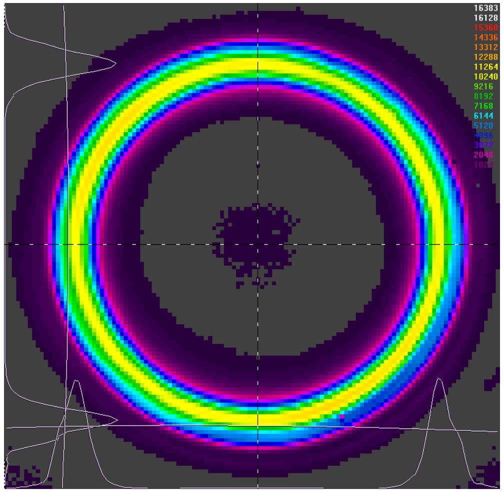
Double Axicon System

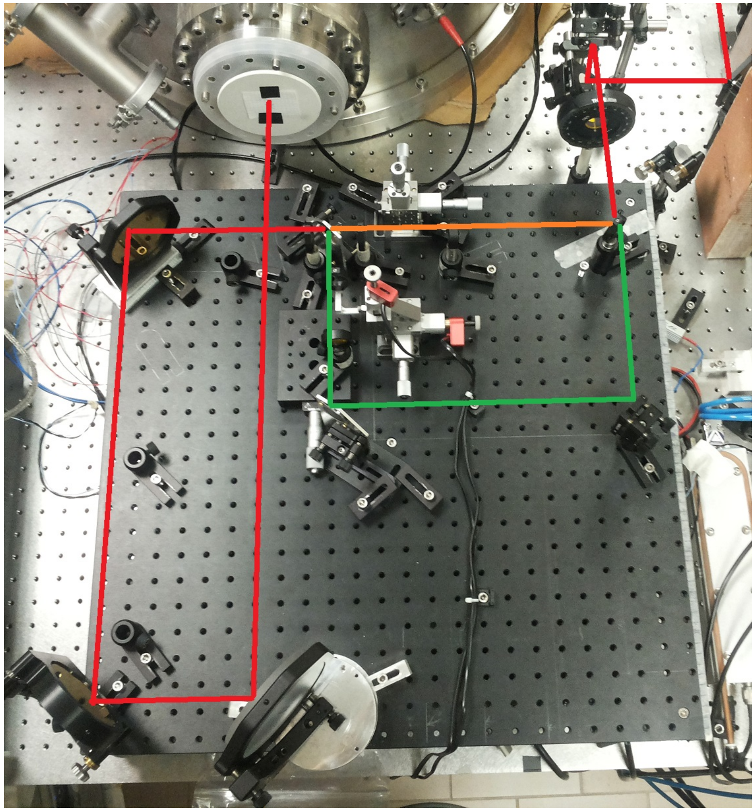


Inner ring



Outer ring

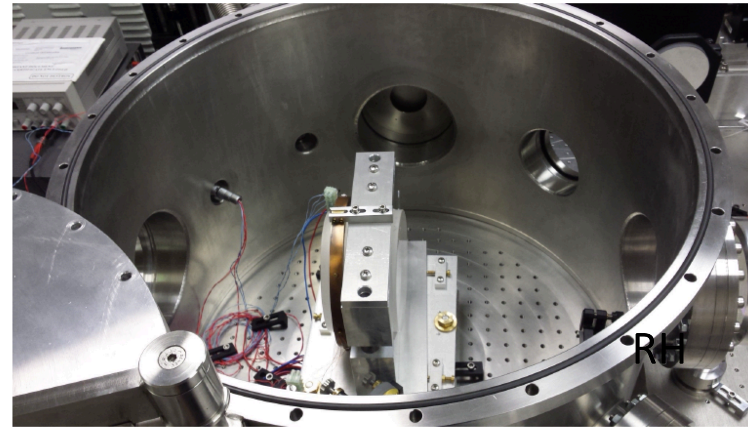


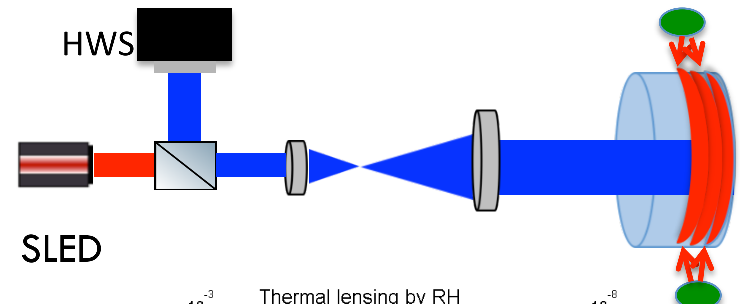


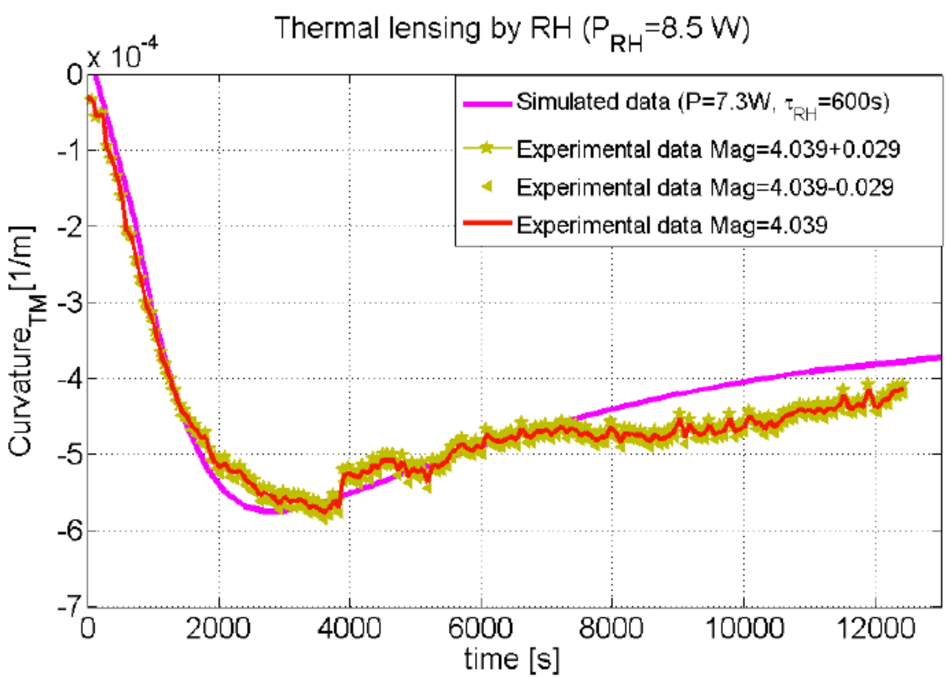
Thermal lensing effect due to the RH

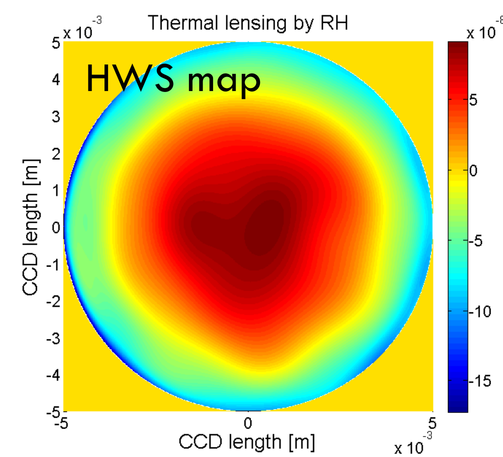
On-axis measurement of the TM curvature due to the increase of OPL inside the mirror compared with the simulated one:

- The error associated to the experimental curve is due to the uncertainty in the telescope magnification;
- The deviation of the experimental behaviour with respect to the simulated one after 2h can probably due to the effect of the thermal drift of the environment.







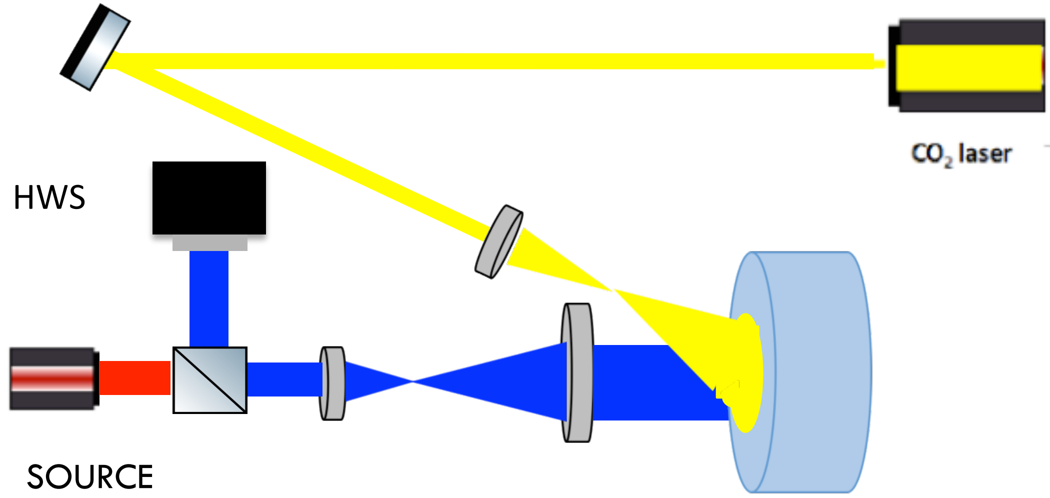


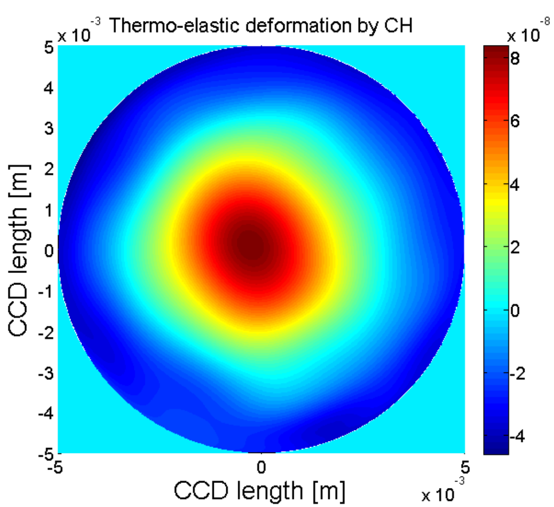
Thermal lensing effect due to the central heating

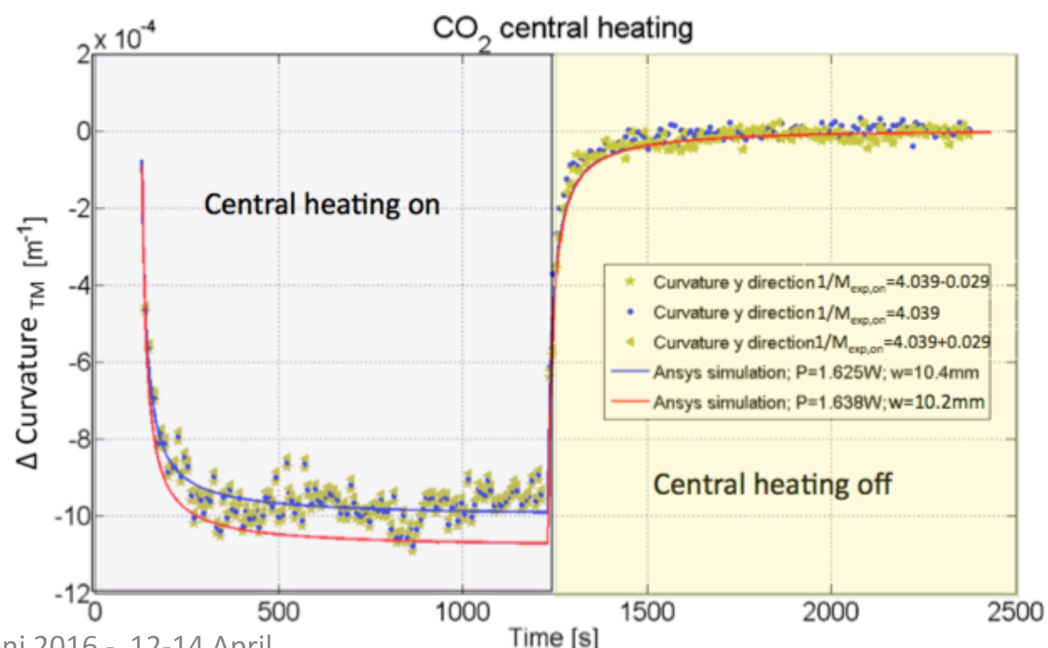
On-axis measurement of the TM curvature due to the CO_2 laser impinging on the TM surface; AOI ≈ 20°: only Y data considered.

All possible error sources accounted for:

- ✓ Telescope magnification;
- ✓ CO_2 power fluctuations;
- ✓ Most relevant source: uncertainty on the CO_2 beam size on TM.



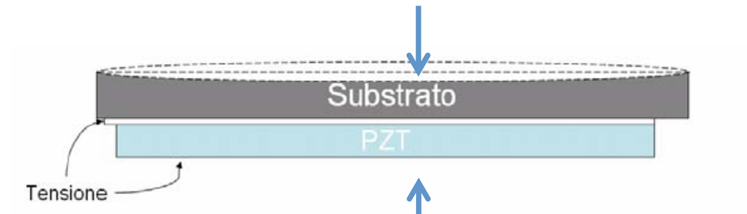




Future generation of actuators

MEMS (Micro Electro-Mechanical Systems)

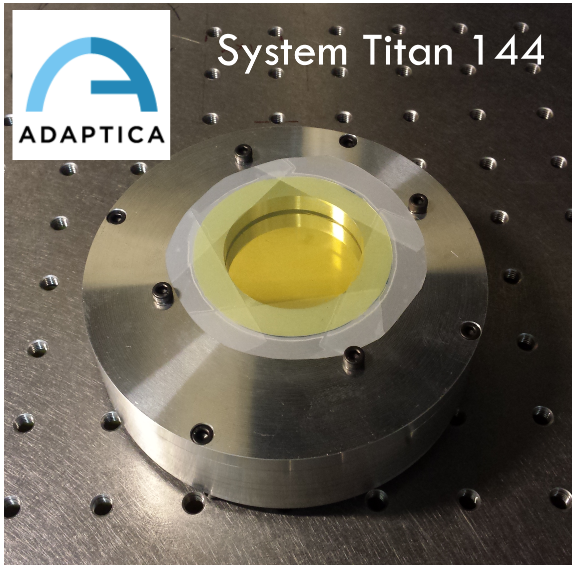
Deformable mirror



Piezo-electrical disk

- ✓ Deformable mirrors to shape the laser beam;
- ✓ Mirror deformation by varying the voltage on the piezo-electrical disks;
- ✓ By varying the voltage applied on the actuators matrix the desired phase profile can be obtained;
- ✓ In Tor Vergata: 12*12 actuators needed to apply corrections over lengths higher than 1 cm (as AdV required), applied on a mirror of 25 mm diameter. Control electronic speed: >1kHz

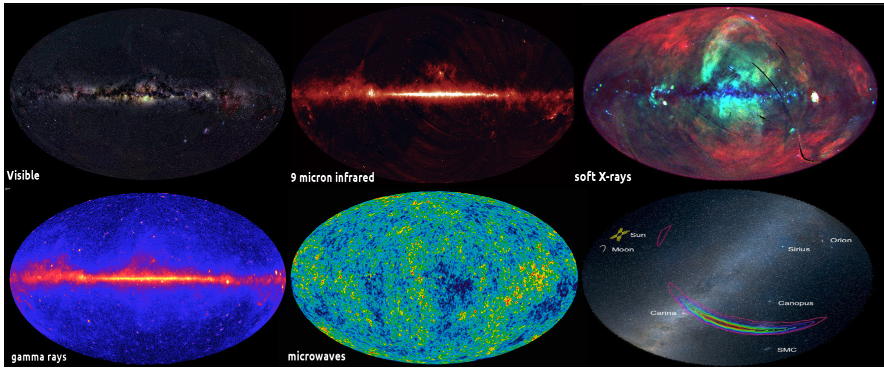
MEMS in Tor Vergata



Summary

NEW

✓ GWs have been detected:
  ○ Gravitational Astronomy started



- ✓ Increase the sensisitivity of our interferometers;
- ✓ Wavefront aberrations are an unavoidable annoying presence:
  - ○ limit both the controllability and the sensitivity of the instrument.
- ✓ High-performance adaptive optical system is fundamental to ensure the full operation of the instrument:
  - ✓ Wavefront sensors
  - ○ Very low noise required;
  - ○ High precision.
  - ✓ Dynamical actuators
  - ○ necessity to generate symmetric heating patterns (DAS, central heating);
  - ○ necessity to generate also non-symmetric heating patterns (laser scanning system, MEMS).

Thank you

$\left[-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}+\nabla^2\right]h_{\mu\nu}=0$
GW150914
t[s]
h