Advanced Optics Research in Gravitational Wave Detection

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ET ITALY Einstein Telescope

ADVANCED OPTICS LAB @ TOR VERGATA FOR ET

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Outline

1. A new era in astrophysics
2. Gravitational Waves detection
    a. Sensitivity curves
    b. Present and future GW detectors (Virgo, LIGO, KAGRA, ET)
3. Core optics: advanced optical technologies
4. Power-induced optical aberrations
    a. Thermal Compensation System
    b. Adaptive optics developments
5. Development of materials for ultra-low loss optical coatings
    a. Candidate materials
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    d. Experimental investigation techniques
6. Conclusions

A new era in astrophysics

- O1: Sept. 2015 – Jan. 2016

GW150914: the birth of GW astronomy

- O2: Nov. 2016 – Aug. 2017

GW170814: the first triple detection
GW170817: the first neutron stars merger detected

- O3a: Apr. 2019 – Sept. 2019

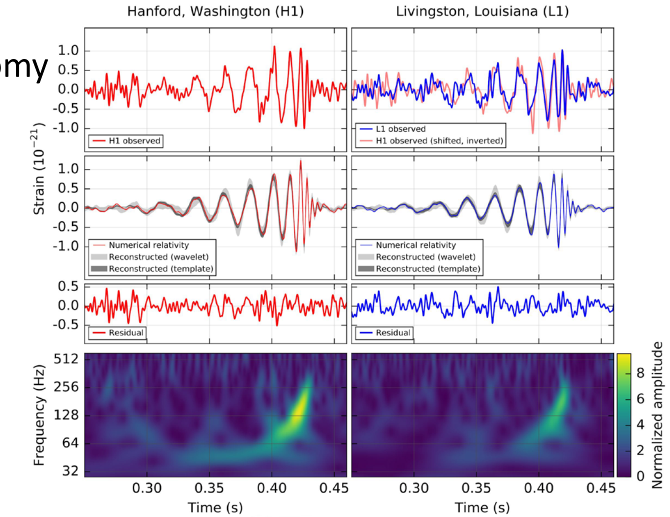
GW190521: BH-BH merger to IMBH

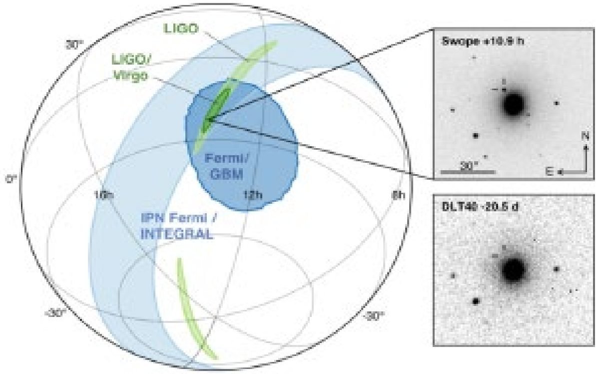
- O3b: Nov. 2019 – Mar. 2020

GW200115: the brightest NS-BH merger

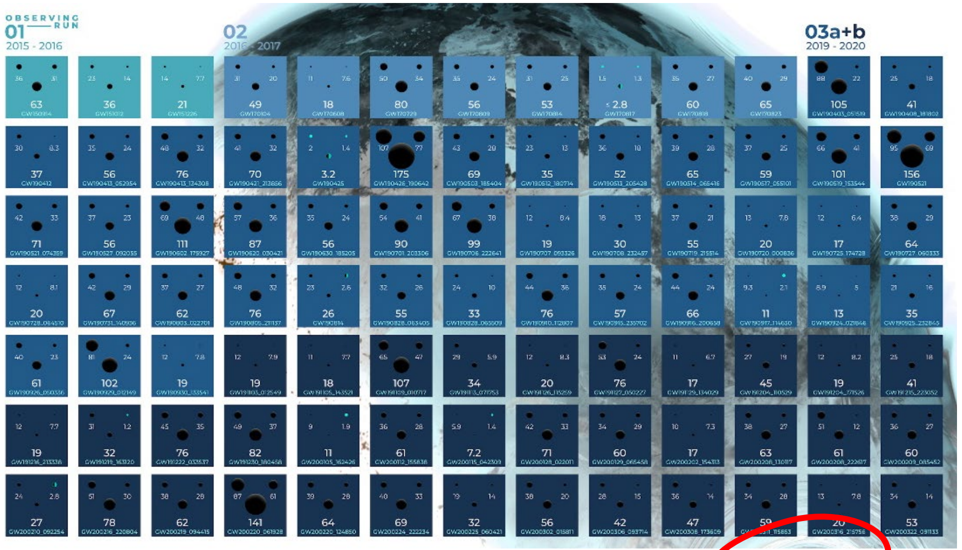
- O4a May 2023 – Jan. 2024

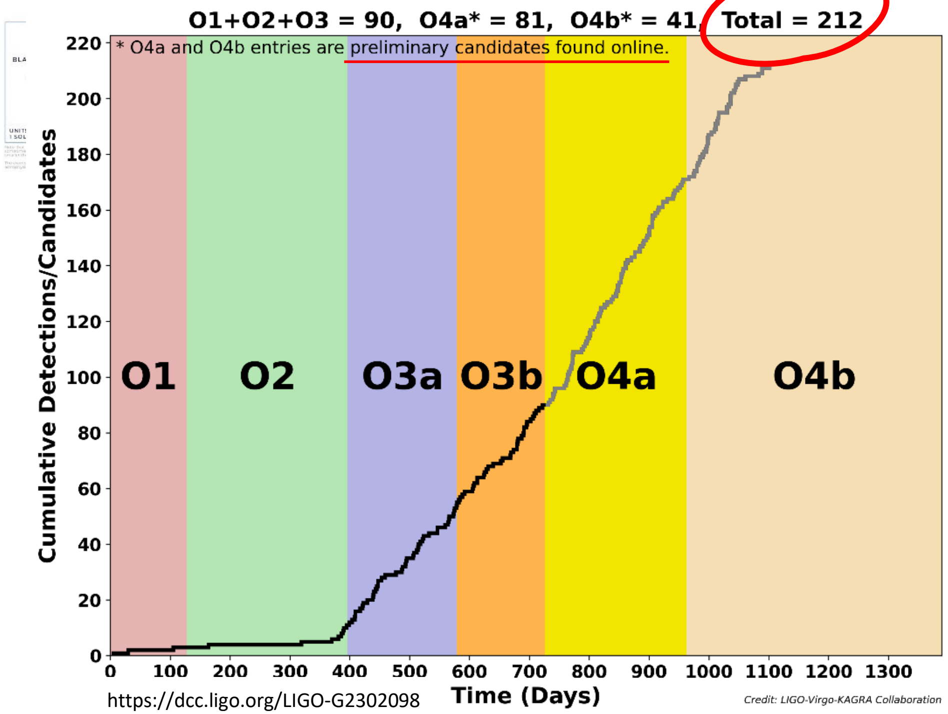
- O4b: Apr 2024 – June 2025
    - LIGO+Virgo
    - Kagra to join in 2025 to complete commissioning



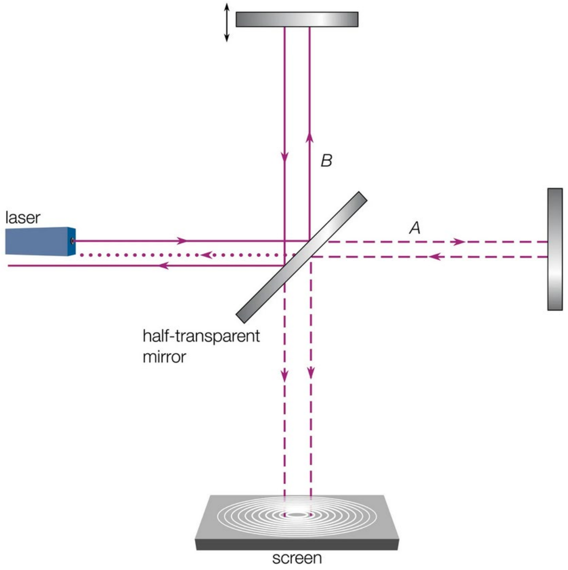


[Credit: LIGO/Virgo/KAGRA/C. Knox/H. Middleton]





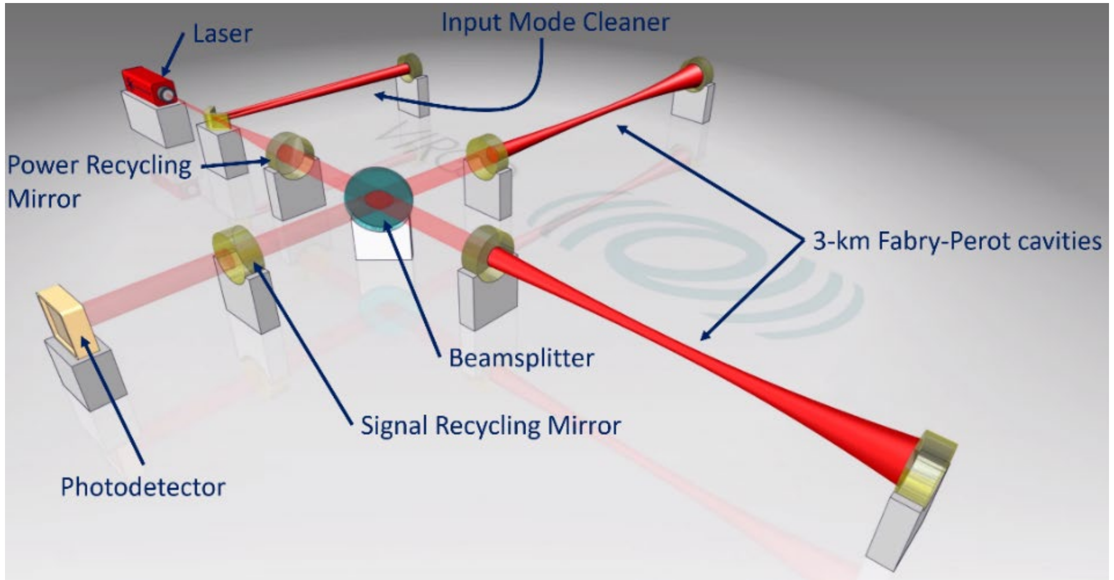
Gravitational wave detection

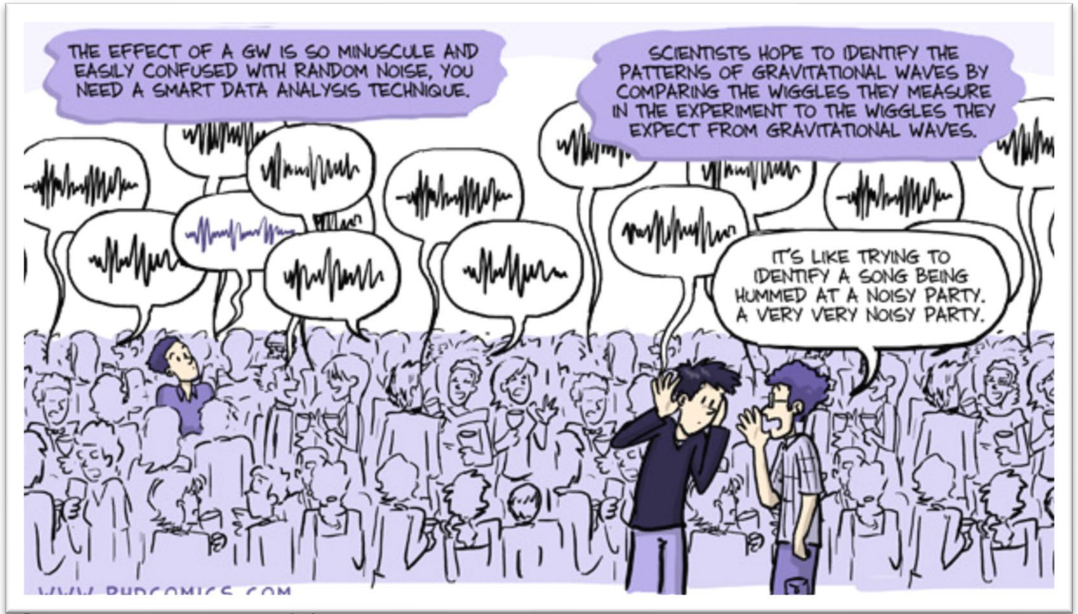


The winning strategy was to **use the light of a laser as a ruler** in an interferometric detector. Simple idea of **Michelson Interferometer setup**, on which many upgrades have been made to further improve its sensitivity.

- *System of freely falling bodies (mirrors)*

- *As a gravitational wave passes, the distance between two bodies subjected only to gravitational forces changes by:* $\Delta L = \frac{1}{2} hL$



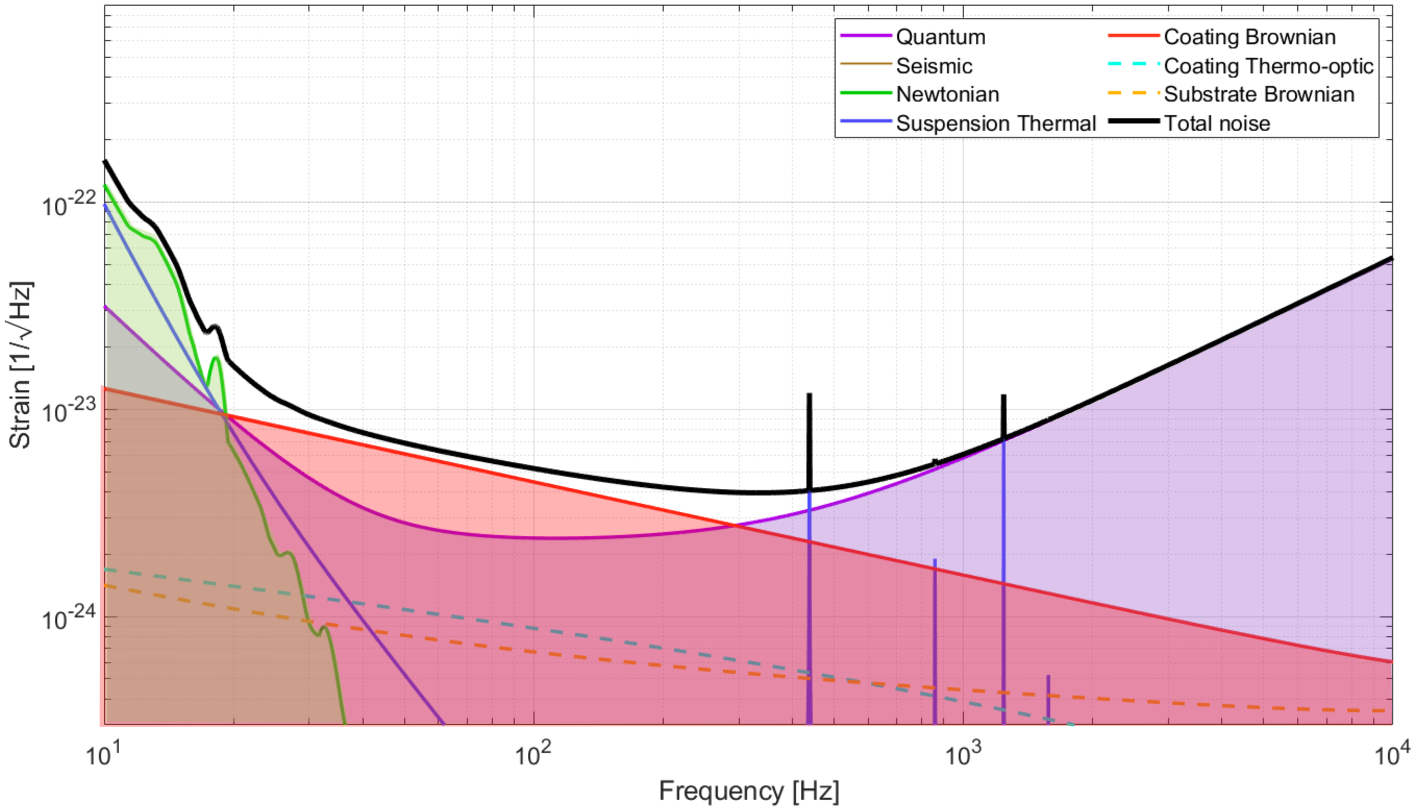


Sensitivity curves

The sensitivity curve of a GW detector reveals its **detection capabilities**, influenced by fundamental and technical noises.

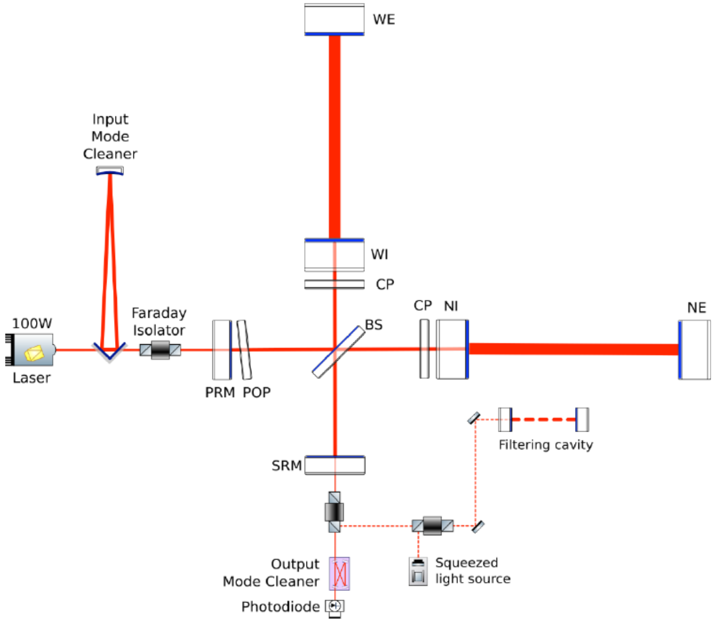
- **Newtonian noise < 10 Hz**
- **Thermal noise ~ 10 - 300 Hz**
- **Shot noise > 300 Hz**

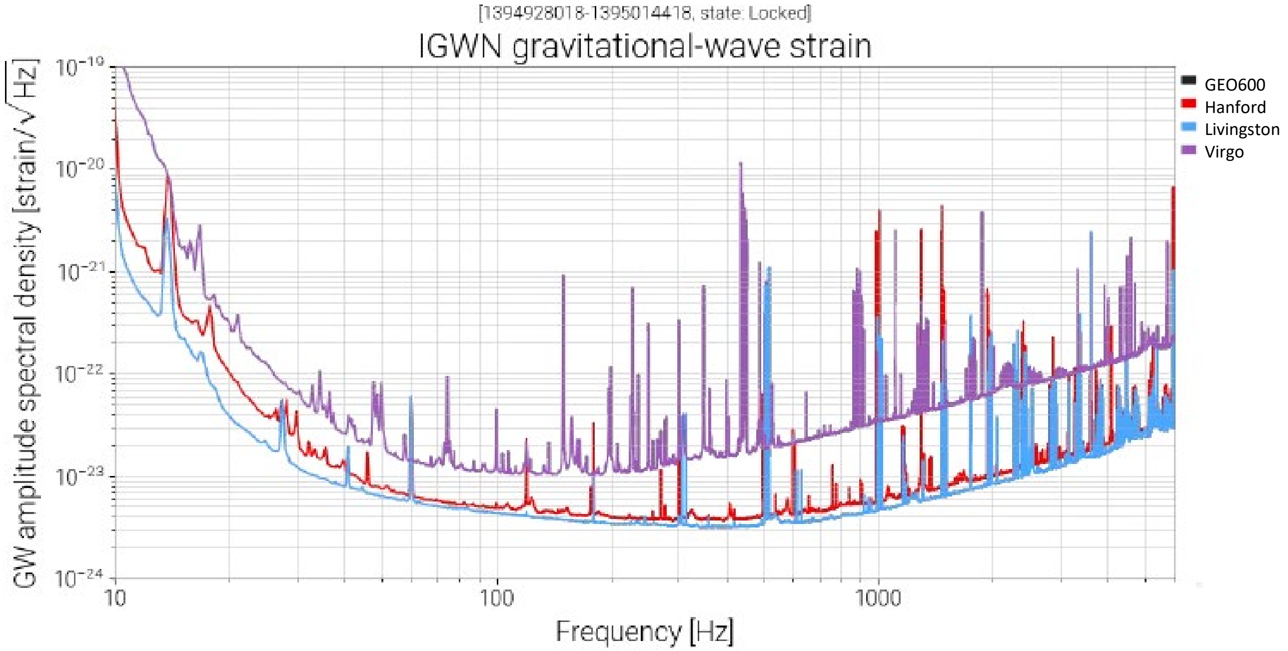
AdV+ project sensitivity curve



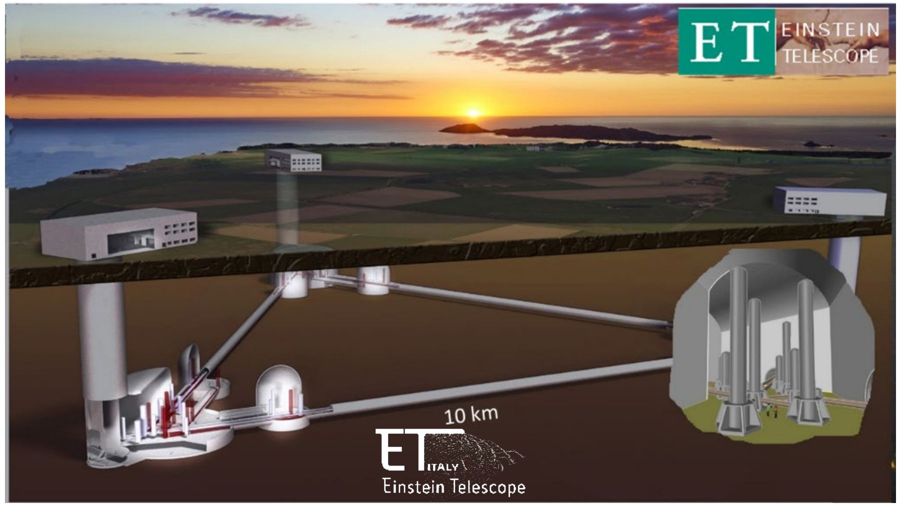
Advanced GW Detectors

- 3 km arm Michelson interferometer tuned at **dark fringe**
- 40 kg, SiO2 substrate
- Circulating TEM_{00} mode from CW Nd:YAG source @1064 nm+ **injected sidebands**
- Optical path folding with **resonant Fabry Perot** arm cavities
- Power-recycled/Signal-recycled configuration
- **High intra-cavity power** build up (~ 200 kW)





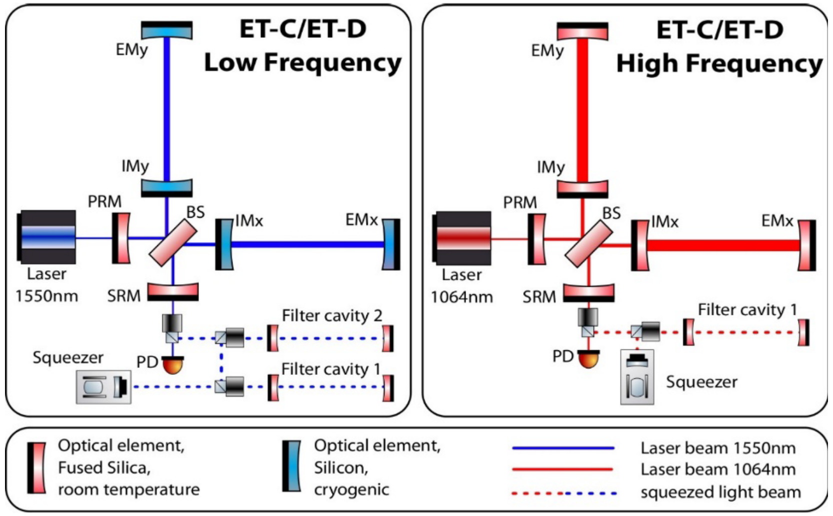
3G detectors

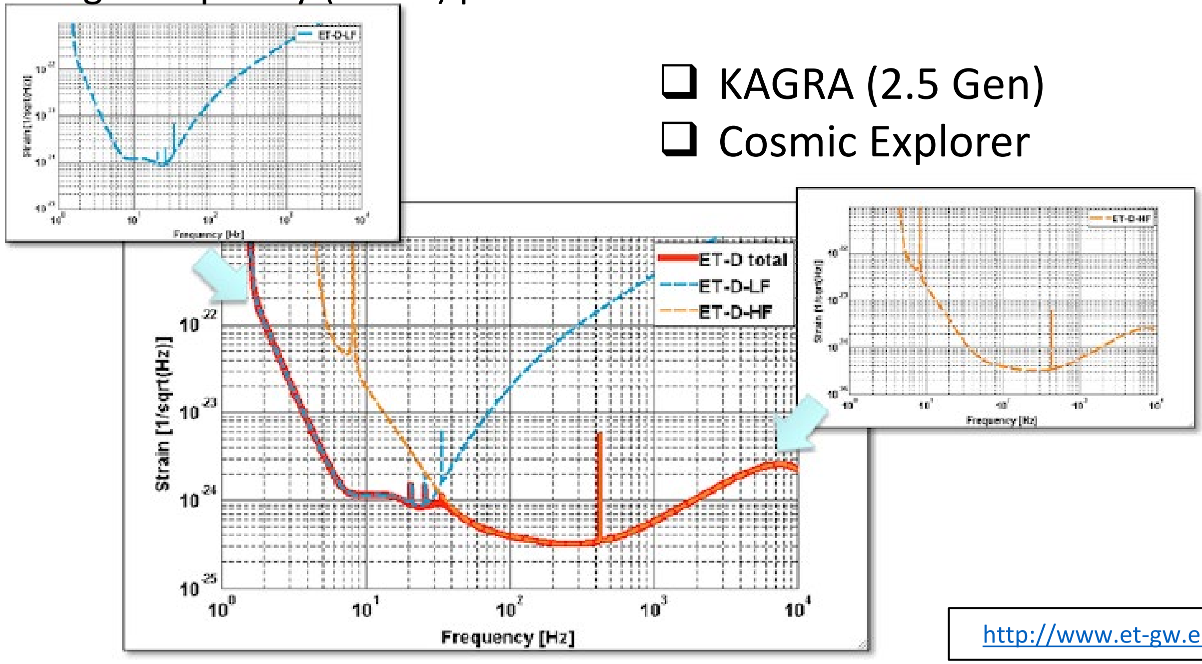


Third-generation, gravitational-wave observatory:

➢ a greatly improved **sensitivity**

- **underground** infrastructure
- **10km** long arms
- **three nested detector**: each will comprise two interferometers, one specialised for detecting low-frequency (**ET-LF**) gravitational waves and the other one for the high-frequency (**ET-HF**) part.
- cryogenic temperature (down to 10 – 20K)
- 200 kg, Si or Sapphire substrate





- ❑ KAGRA (2.5 Gen)
- ❑ Cosmic Explorer

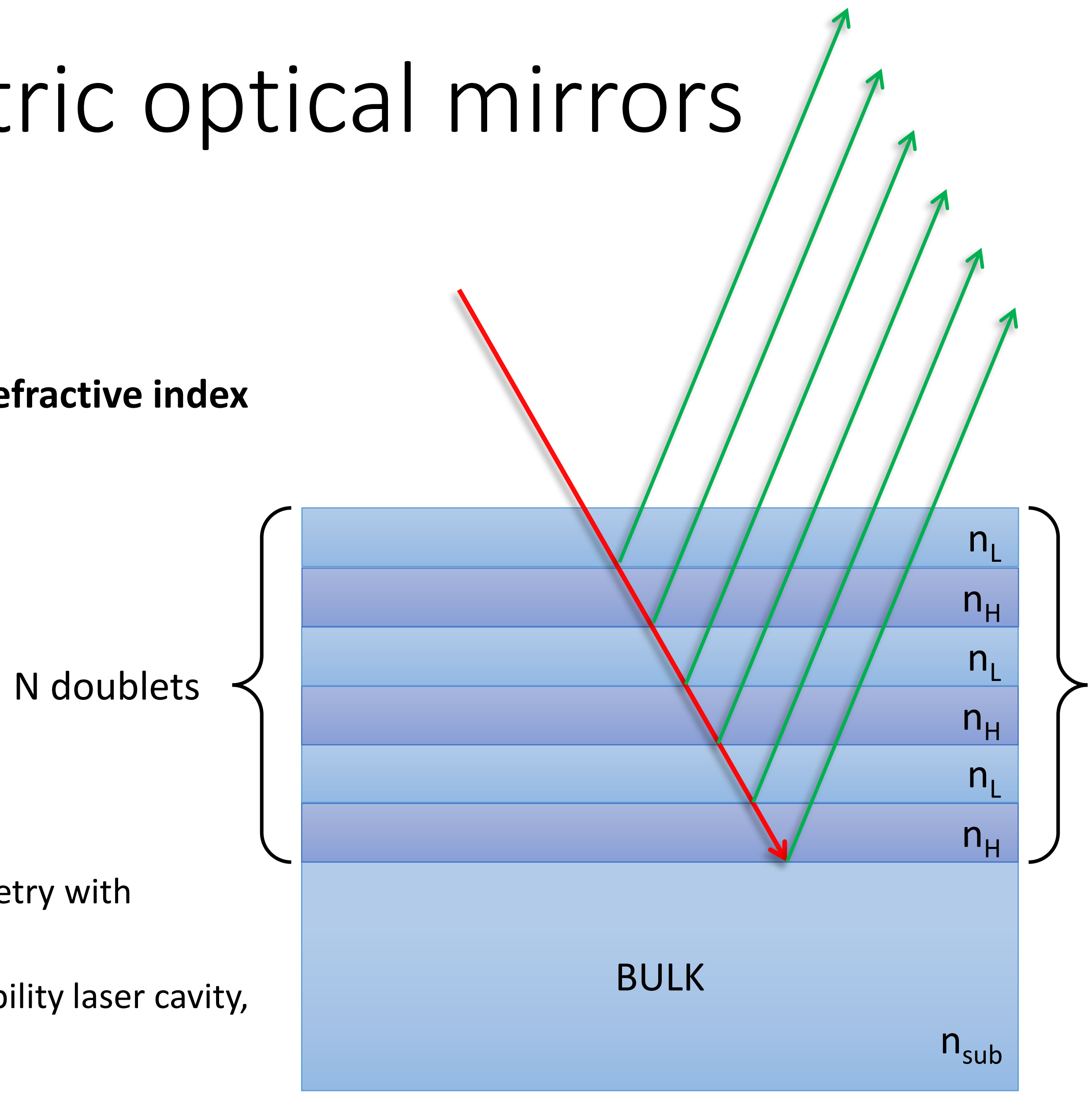
http://www.et-gw.eu/

Core optics – dielectric optical mirrors

Bragg reflectors

- Bulk + multi-layer reflective coatings
- A stack of **alternate layers of high- and low- refractive index materials**
- Accurate choice of **thickness** $\cong {}^{\lambda}/_{4}$
  - Constructive interference
  - High-quality reflector

$$r = \frac{1 - n_{sub}\left(\frac{n_L}{n_H}\right)^{2N}}{1 + n_{sub}\left(\frac{n_L}{n_H}\right)^{2N}}$$

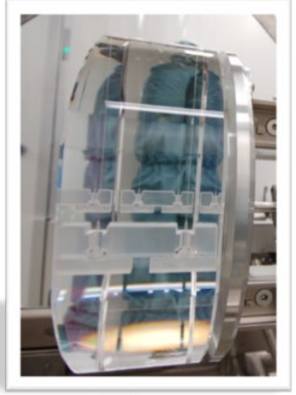


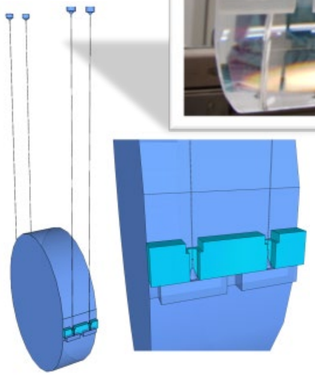
Many high-precision experiments use laser interferometry with resonant optical cavities:

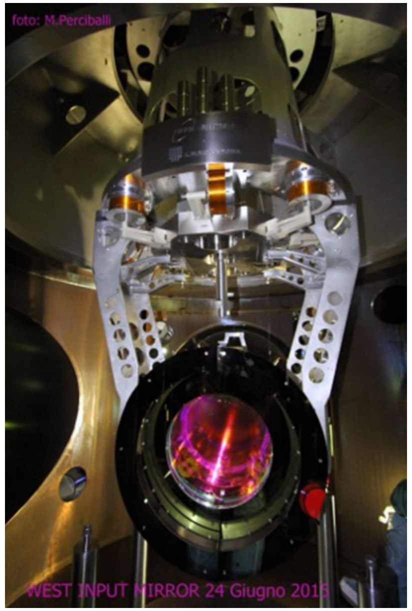
<u>*Gravitational wave interferometry*</u>, high frequency stability laser cavity, atomic spectroscopy, atomic clock, …

Core optics – state of the art

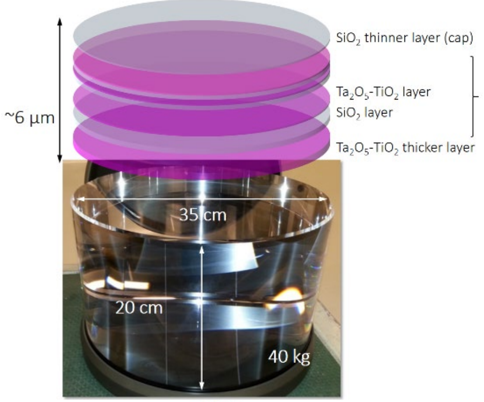
- Test masses (mirrors) in AdV+:
  - made with high purity **fused silica,** SiO_2
  - diameter 35 cm, 40 kg
- **Suspended** to filter out seismic motion, in a **quasi-monolithic fused silica arrangement**, in vacuum
- **Multi-layered coating** made of amorphous oxides (TiO_2:Ta_2O_5/SiO_2) with very low absorption < **ppm**





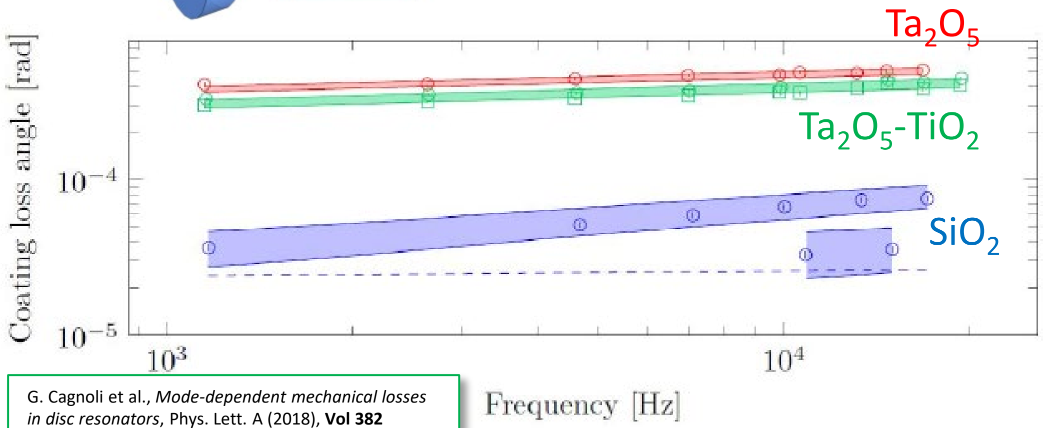


Flatness	Thickness uniformity	Absorption	Scattering
<0.5 nm RMS (within ⊘ 150 mm)	0.05 (within ⊘ 150 mm)	<0.4 ppm	<10 ppm



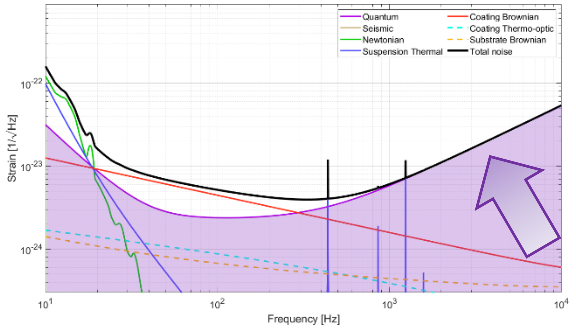
Coating material	Ta_2O_5-TiO_2	SiO_2
n (at 1064 nm)	2.09±0.01	1.45±0.0
ρ_c [g/cm^3]	6.65±0.07	2.20±0.04
a [10^{-4} rad Hz^{-b}]	1.43±0.07	0.20±0.04
b	0.109±0.005	0.030±0.024
$\mathcal{Y}_c$ [GPa]	120±4	70±1
ν_c	0.29±0.01	0.19±0.01

Table 3.2: Optical and mechanical parameter of present coating materials [79]: the loss angle can be extrapolated from a and b parameters and is based on the frequency dependence $\phi_{coat}(f) = af^b$.

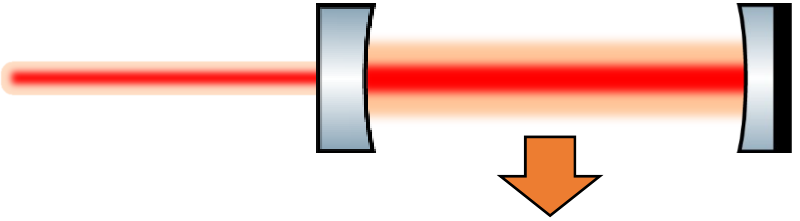


G. Cagnoli et al., *Mode-dependent mechanical losses in disc resonators*, Phys. Lett. A (2018), **Vol 382**

AdV+ project sensitivity curve



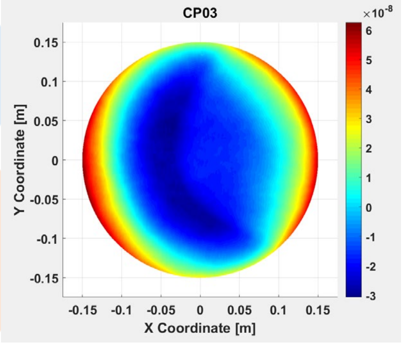
Power induced optical aberrations



Power absorbed in optics $\lesssim$ **100 mW**

Sources

- ➢ imperfections in the production process of the mirrors (**cold defects**);
- ✓ absorption of optical power in the coatings and substrates of the optics (**dynamical effects**).



- ➢ Inhomogeneity of refractive index, impurities …
- ➢ Manufacturing errors (mismatch of radius of curvature, …)

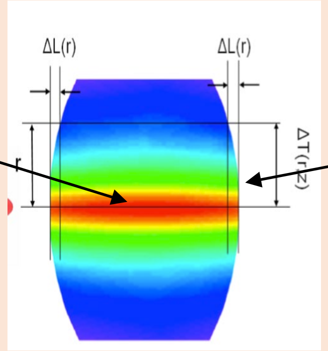
Effects

Thermal lens

✓ **Thermal lensing**

$$\Delta OPL_T = \frac{dn}{dT}\int_S \Delta T ds$$

OPL distortions due to dependence of **refractive index** from temperature variation



✓ **Thermo-elastic effect**

$$\Delta OPL_R \approx 2\alpha \int_0^h \Delta T\, dz$$

Change of radius of curvature (RoC) of mirrors due a non-zero material's **thermal expansion coefficient.**

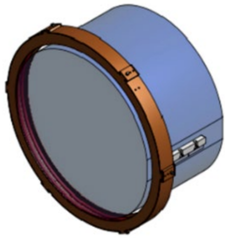
Thermal Compensation System (TCS)

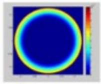
- **Strategy**: introduce a **complementary distortion** with respect to the main laser one, restoring the nominal optical configuration.

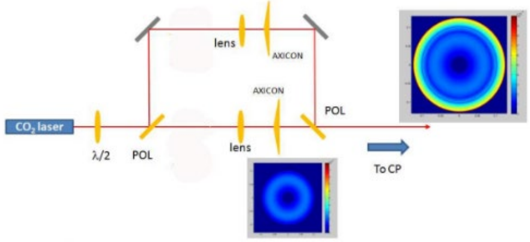
dynamical adaptive optical system

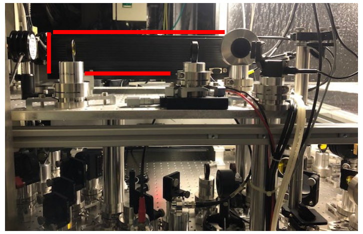
TCS actuators :

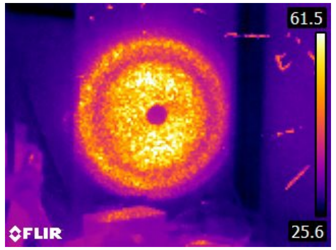
- ✓ CO_2 laser projector (**50 W & 10 W**)
  - ✓ Axisymmetric center & annular patterns
- ✓ Ring Heaters on AR surface







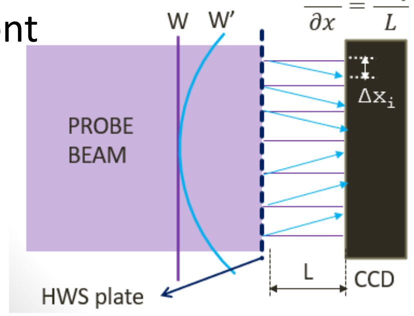


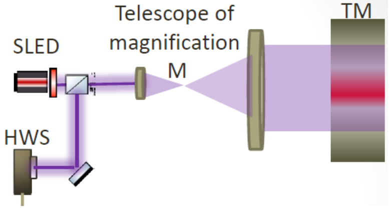


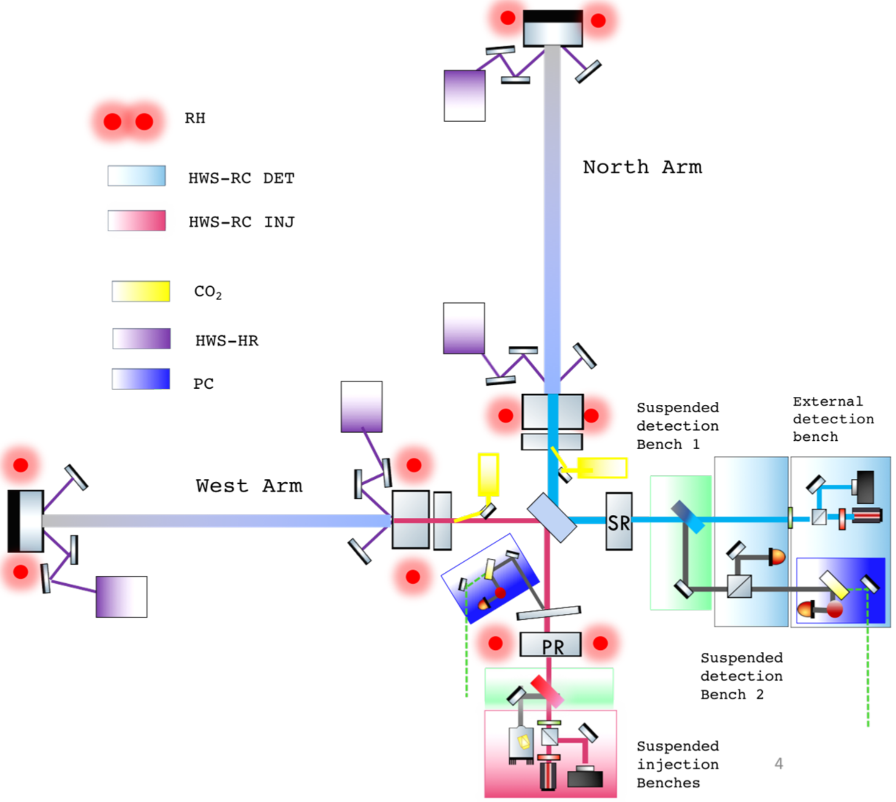
TCS sensing :

- ✓ Hartman Wavefront Sensors (HWS)
- ✓ Phase Cameras

$$\frac{\partial W}{\partial x} = \frac{\Delta x_i}{L}$$





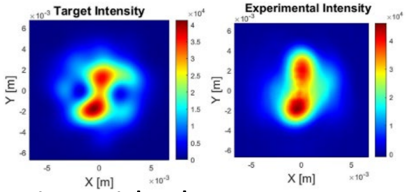


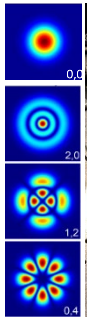
Future adaptive optic developments

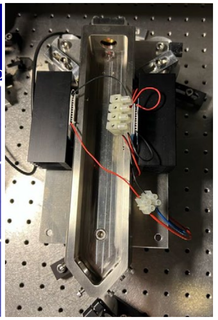
The TCS has proven to be more **versatile** than originally anticipated, showing utility in various contexts.
Adaptive optics, with its *flexibility*, will be a key feature in future detectors:

1. Increased laser power will amplify the impact of ***residual optical aberrations***;
2. Readiness to address ***unexpected defects*** and compensate for operational aberrations not accounted for in the initial design;
3. The need for ***independent actuators*** to prevent interference and ensure efficient compensation.

➢ **Deformable Mirror (DM)**
- imprint a phase on CO2 beam to obtain the **desired intensity pattern**
- Correction of non axisymmetric residual

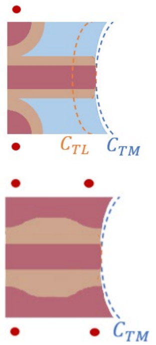


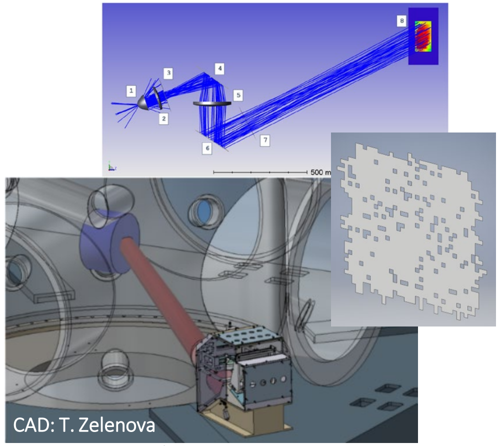




➢ **CO_2 Mode Cleaner (MC)**
- Efficiency of DAS correction strictly related to the laser beam quality
- TEM_{00} Gaussian VS **High Order Modes**
- Mode cleaner cavity for high power CO_2 laser has never been realized before

➢ **Double RH**
- RH introduces a thermal lens (C_{TL}) inside the bulk
- The C_{TL} could be compensated, placing a **second RH near the HR surface**, such that the OPL is almost constant along the thickness.

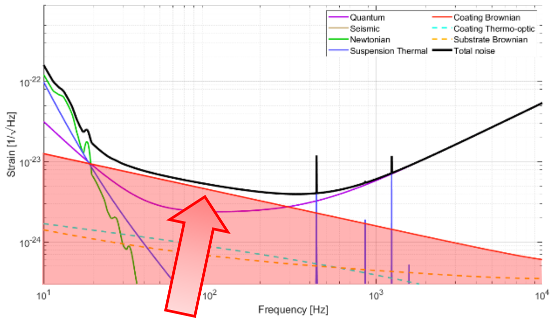




➢ **Point Absorbers (PA) mitigation**
- **Highly absorbing areas** on the coatings of the core optics
- The corrective heating pattern is reproduced by a **binary mask illuminated by a thermal source**, with each hole acting as an actuator.

Coating thermal noise

AdV+ project sensitivity curve



- Coating thermal noise (CTN) limits the detection in the middle frequency bandwidth
- The key parameters are:

Temperature — Mechanical loss — Coating thickness

$$\mathrm{CTN}(f) \propto \frac{\sqrt{\frac{T}{f}\frac{1}{{w_b}^2}\varphi\, t_{coat}}}{L}$$

Arm length — Beam-size

V_nEXT (post O5) upgrades:

Larger beams on end test masses

- 6 cm radius ⇒ 10 cm radius

➢ **Larger end mirrors**
  - 35 cm diameter ⇒ 55 cm diameter
  - 40 kg ⇒ 100 kg
  - New suspensions/seismic isolators for large mirrors

New mirror coatings

- Lower mechanical losses by a factor 3, less point defects, better uniformity

3° generation detectors (ET):

Cryogenic temperature (down to 10 – 20K)

10km long arms

Larger beams on larger test masses

New mirror coatings

Development of materials for ultra-low loss optical coatings

GOAL:

increase the mechanical performances of today's reflective coatings, retaining their outstanding optical and morphological properties

Candidate materials

Trial and error approach VS systematic approach

- deeper understanding of the **underlying physical mechanisms driving the losses**

<u>Amorphous materials</u>

Overall disordered structure, locally arranged.

Dissipative mechanism

- *<u>Two Level System (TLS)</u>*: *metastable states* separated by an energy barrier

- Floppy (optimal distribution of TLS) materials
  - $TiO_2:GeO_2$, $TiO_2:SiO_2$
- Stiff (reduced number of TLS) materials
  - SiN, aSi

<u>Crystalline coatings</u>

Band gab free of localized states, dissipative mechanisms are limited

- transfer and maximum available size; development costs are currently a major limitation

- GaAs/AlGaAs, crystalline coatings

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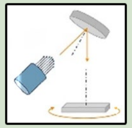

Different deposition methods and fine-tuning deposition parameters

- Ion Beam Sputtering (IBS)
- Magnetron Sputtering (MS)
- Chemical Vapor Deposition (CVD)
- Molecular-beam epitaxy (MBE)

Post-deposition treatments

Annealing

- improve the **atomic organization** of the coating in the medium-range order and reduce its mechanical loss angle
- modify the **chemical composition** (desorption of contaminants)
- **controlled crystallization**

Mixing

- **Enhances material properties** (like refractive index and mechanical losses)
- **Prevents crystallization**, allowing for higher annealing temperatures.
- **Reduces stress**

❖ Introduces an **additional variable** that must be precisely managed during fabrication

Development of materials for ultra-low loss optical coatings

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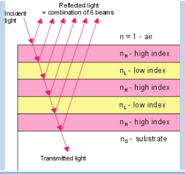
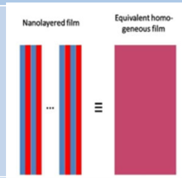
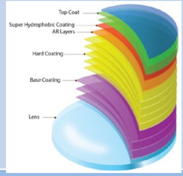
Coating structure and design



__Bragg reflectors__: thickness optimization, to maintain the desired reflectivity and reduce coating thermal noise (CTN)



__Nano-layering__: periodic stack of ultrathin (nanometer-scale) films that behaves like a homogeneous material with a tunable refractive index. It can be annealed at higher temperatures, thanks to geometrical suppression of crystallization



__Multimaterial approach__: Combination of different materials with low optical absorption near the surface and minimized mechanical losses deeper within

Development of materials for ultra-low loss optical coatings

GOAL:

increase the mechanical performances of today's reflective coatings, retaining their outstanding optical and morphological properties

Candidate materials → ***Coating deposition techniques and treatments*** → ***Coating structure and design***

Investigation techniques:

- *Optical properties*: measurement of optical absorption and/or extinction coefficient and refractive index (spectroscopic ellipsometry)
- *Mechanical dissipation properties*: measurement of loss angle and substrate preparation procedure (thermal annealing and polishing of barrel), density and elastic constants (Brillouin spectroscopy); numerical simulations (molecular dynamics, FEA)
- *Microscopic structure*: chemical composition and stoichiometry (XPS), crystallization (XRD, Raman spectroscopy); local molecular structures (Raman sp.); topology and surface composition (AFM and SEM)
- *Thermal and opto-thermal properties*: optical path as a function of temperature (thermo-refractive measurement); measurement of the coefficient of linear thermal expansion (Curvature measurement)

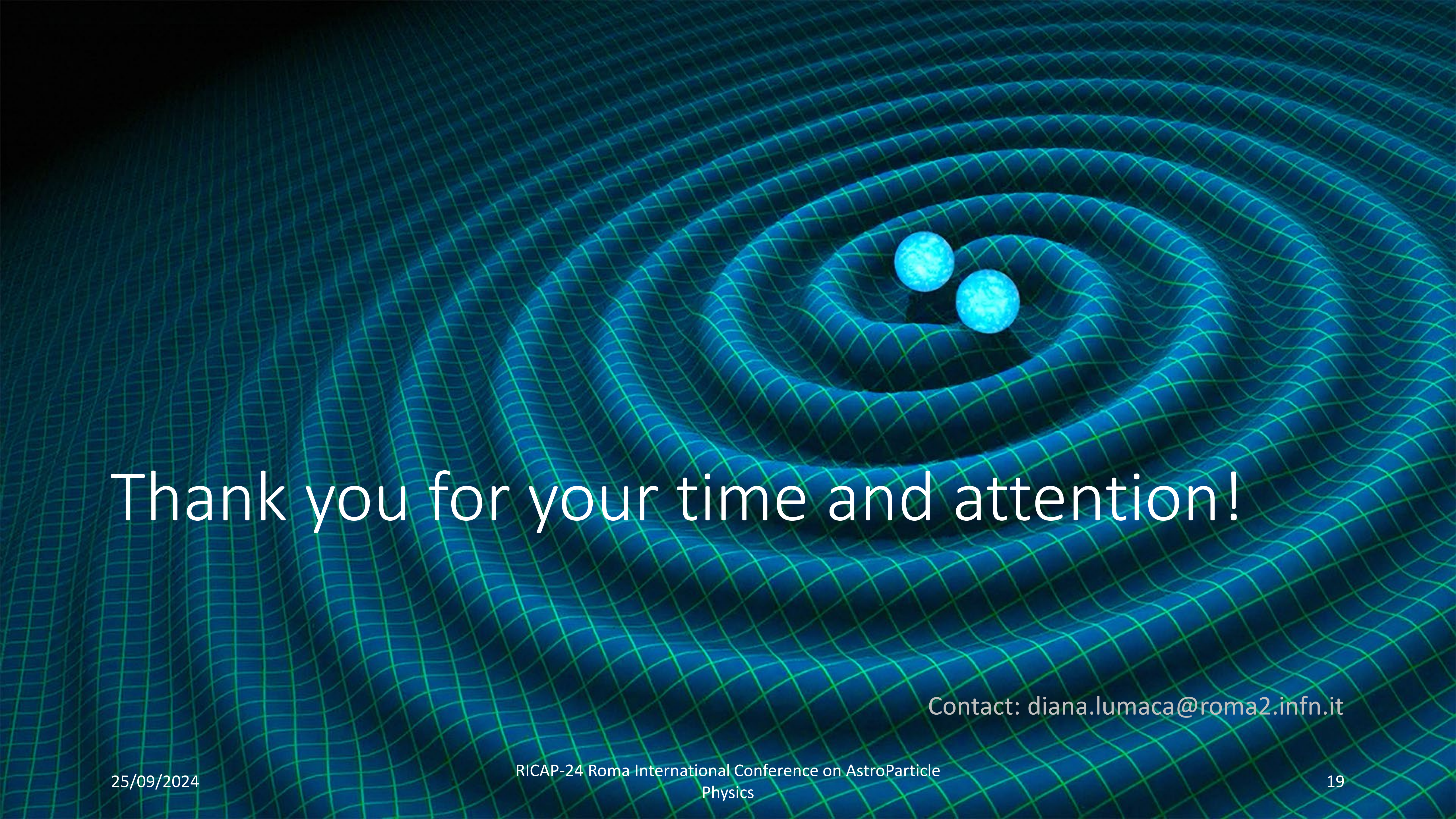
➢ ***Comprehensive picture of the relevant physics of a given material***

Conclusion

- **Current** coatings are **the best optical component ever manufactured so far**, in terms of excellent surface figure, really low absorption, very low scatter.
- **Improvements** are still needed to tackle with:

➢ **Power induced optical aberrations**
  - Introduce a complementary distortion with respect to the main laser one with TCS
  - Improve **aberration identification and correction** of non axisymmetric residual and point-like defects
  - Ready to address **unexpected defects** and compensate for **operational aberrations** not accounted for in the initial design
  - **Indipendent actuators** to prevent interference and ensure efficient compensation

➢ **Coating thermal noise**
  - Many knobs for reduce CTN (T, thick, beam size, loss angle)
  - **Ultra-low loss material research**
    - Chose candidate materials with systematic approach
    - Coating deposition techniques and treatments
    - Coating structure and design
    - Extensive experimental investigation techniques



Thank you for your time and attention!

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