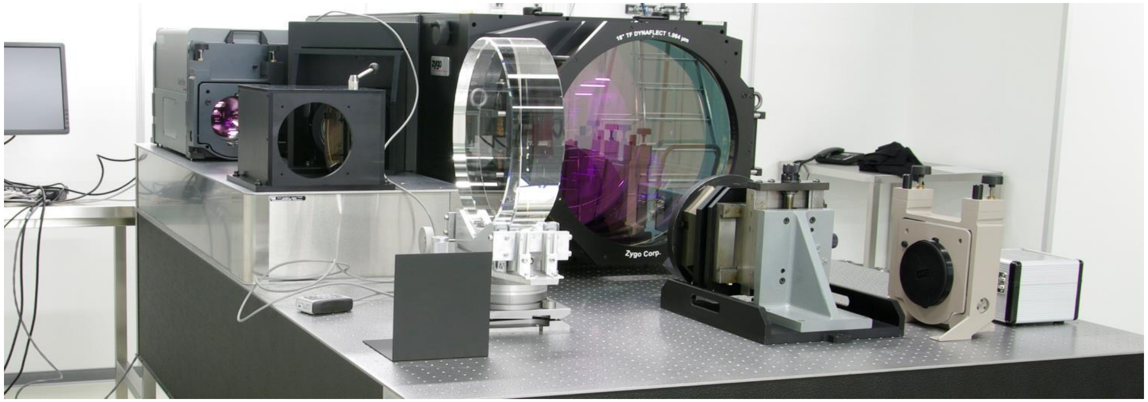
# Fabrication des miroirs pour VIRGO

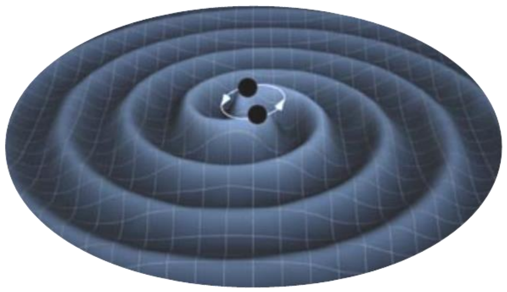
## Journées Techniques Détecteurs IN2P3

1 juin 2021

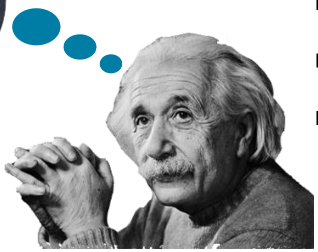
Benoît Sassolas pour le LMA



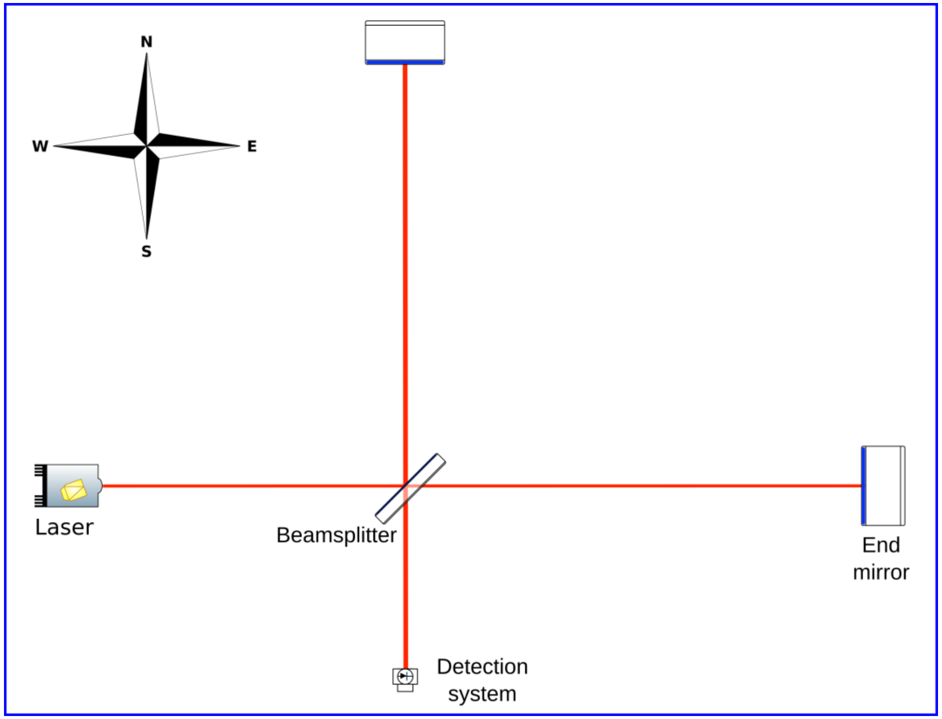
# Gravitational waves



*Example : massive objects merger*



- General Relativity (1915)
- Gravitationnal waves = space-time perturbations
- Came from masses acceleration
- But very tiny signal : $\Delta L/L \sim 10^{-21}$



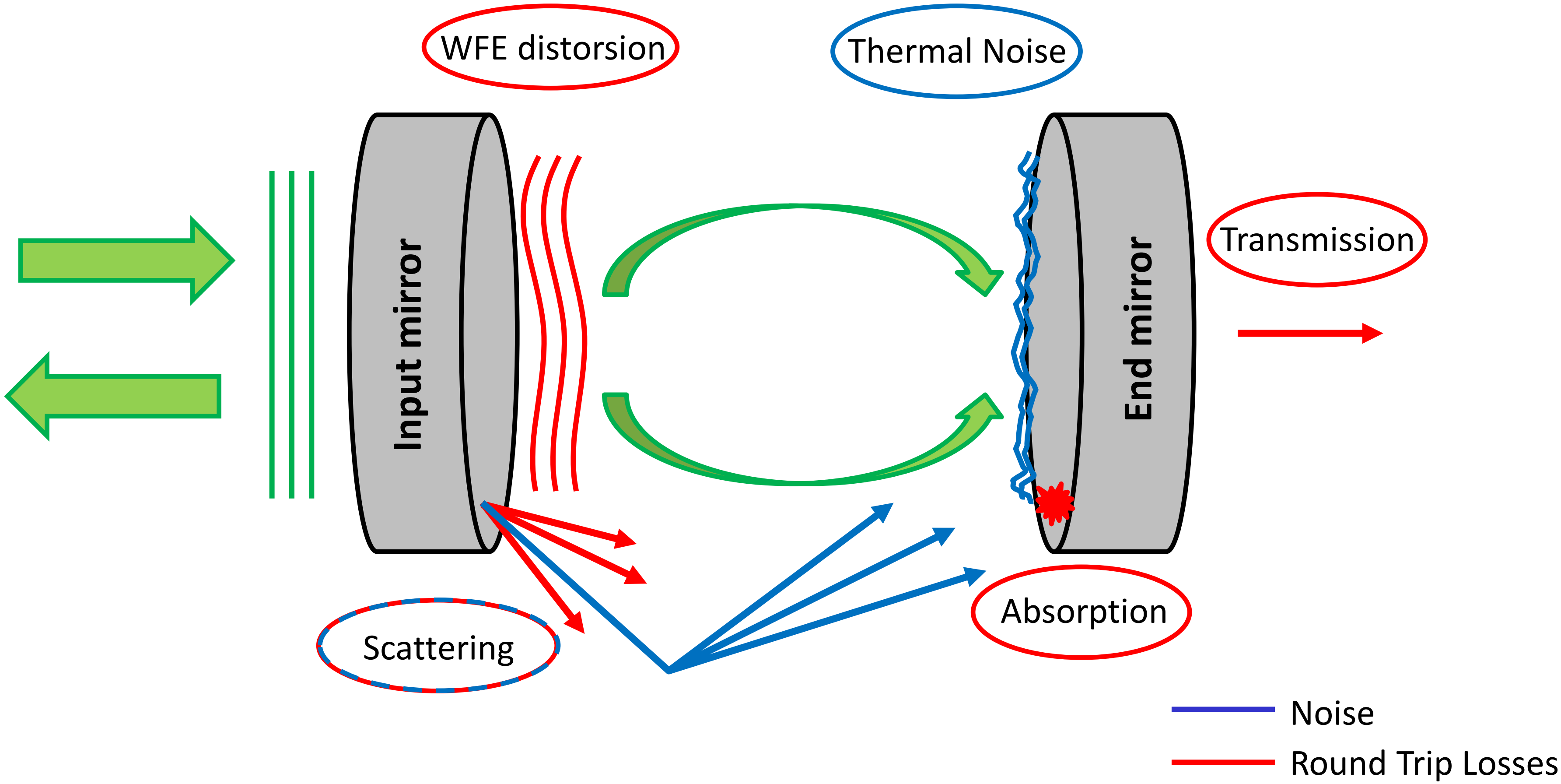
# Giant detectors

Michelson interferometer :

- 3 km length
- Fabry-Perot cavities
- Vacuum <$10^{-9}$ mbar
- 700 kW of light inside the cavity
- 40kg mirrors (Ø 35 cm; 20 cm thick)

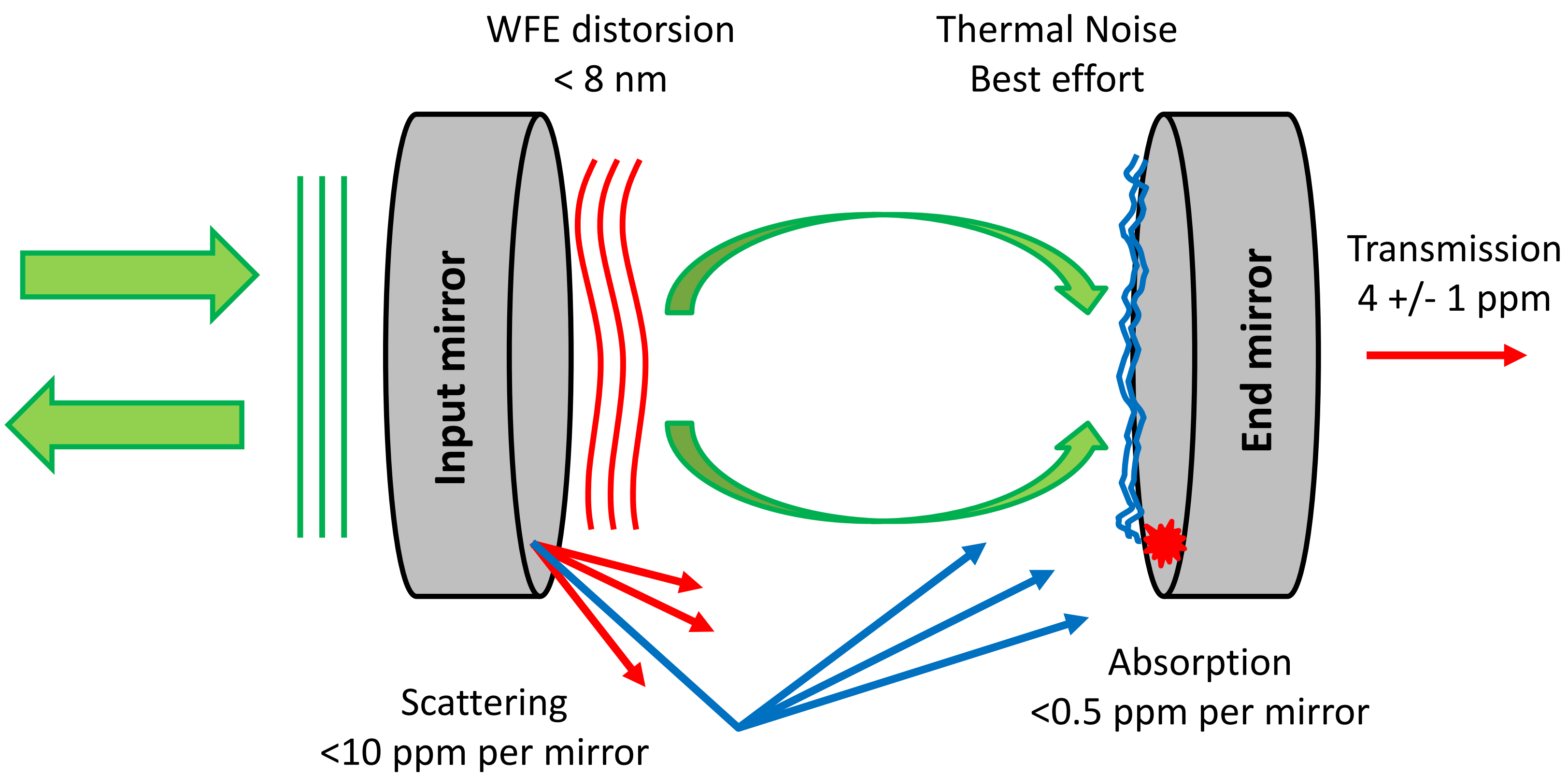
# Major effects in a cavity

Goal : reflect the ligh properly as much as possible but …

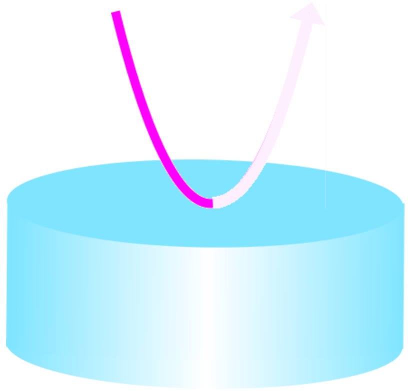



In order to limit these effects,
the mirror must be as performant as possible

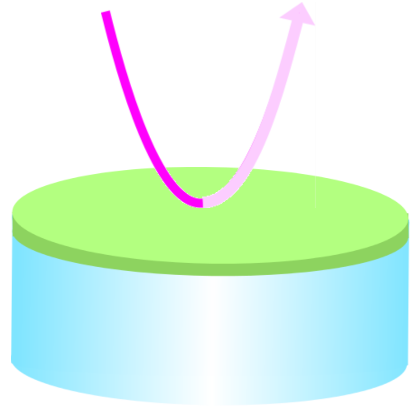
# Requirements



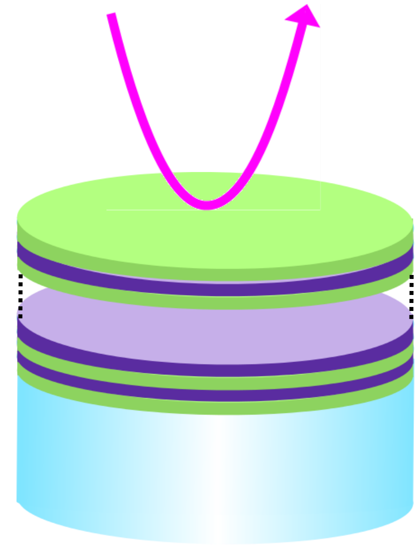
# How does a mirror work ?



1 surface, R ~4 %



2 surfaces, R~20%



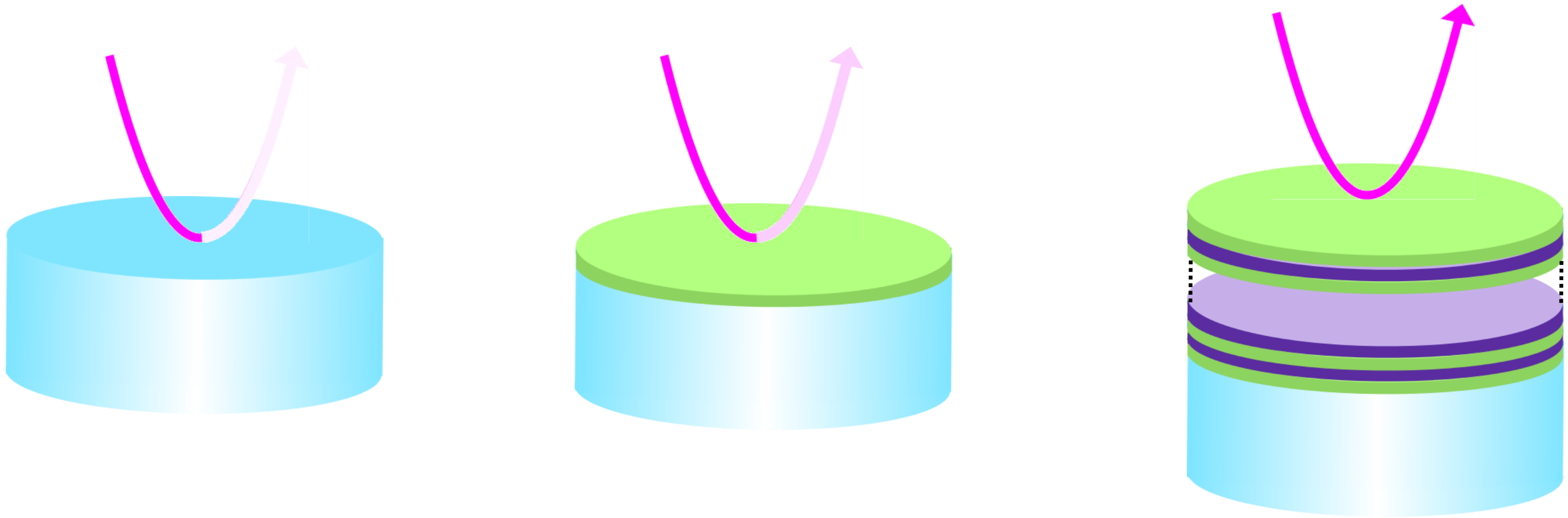
40 surfaces, R~100%

$$R_{max} \cong 1 - 4n_S \left(\frac{n_L}{n_H}\right)^{2p}$$

Stack of thin films :

- 2p layers
- High index material : titania-doped tantala ($Ti{:}Ta_2O_5$)
- Low index material : silica ($SiO_2$)
- Constructive interferences in reflection $\varphi_1 = \varphi_2 = \varphi_3 = \pi\ [2\pi]$
- Thicknesses of the layers $n_H e_H = n_B e_B = \lambda/4$ ; i.e. Quarter Wave Layer (QWL)

# How does a mirror work ?



Developped at LMA for 10 years.
The best optical and mechanical  material so far !
A huge topic in itself !

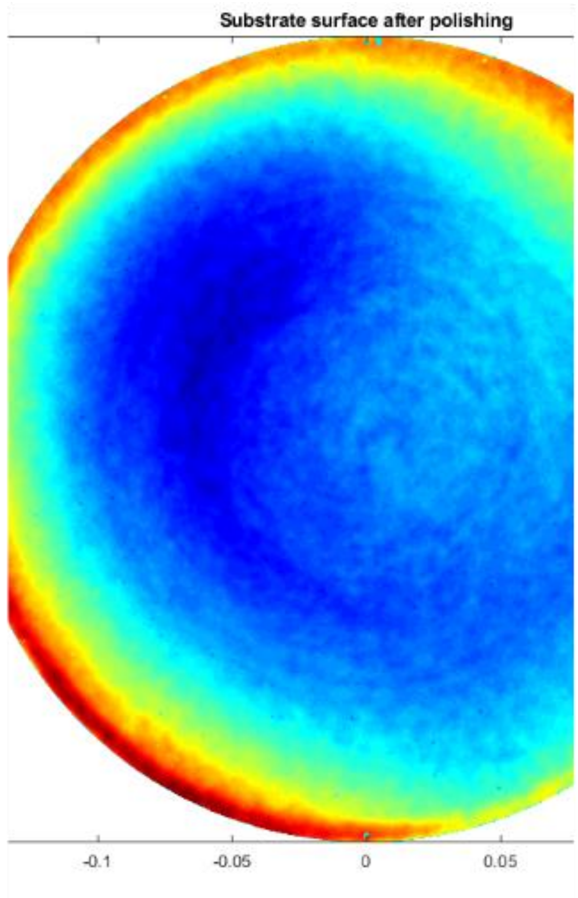
titania-doped tantala (Ti:$Ta_2O_5$)


Harry et al 2006 Class. Quantum Grav. 24 405
Flaminio et al 2010 Class. Quantum Grav. 27 084030
Amato et al 2019 J. Phys. Mater. 2 035004
Granata et al 2020 Class. Quantum Grav. 37 095004 ...

# High performance means high quality

Substrate

Polishing



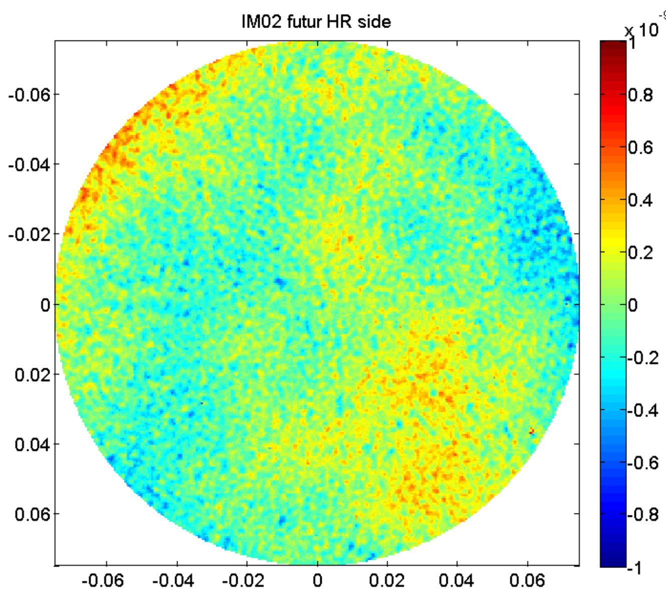

Coating

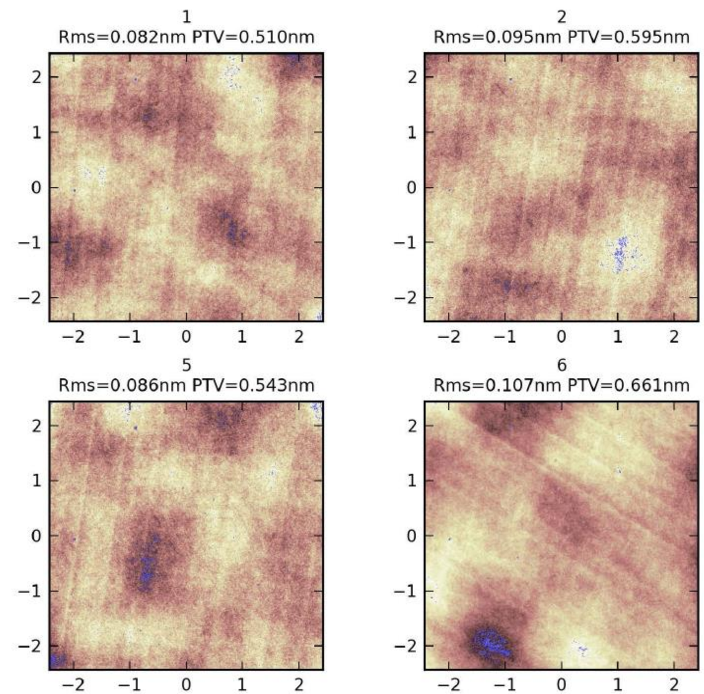
All 3 ingredients need to be exceptional !

# The most perfect piece of glass !

Material
- Ø35 cm ; 20 cm thick
- High purity fused silica
- No bubble or inclusion

Polishing
- RoC = 1.5km +/- 2m
- Flatness PV=λ/300
- Roughness < 0.1 nm rms

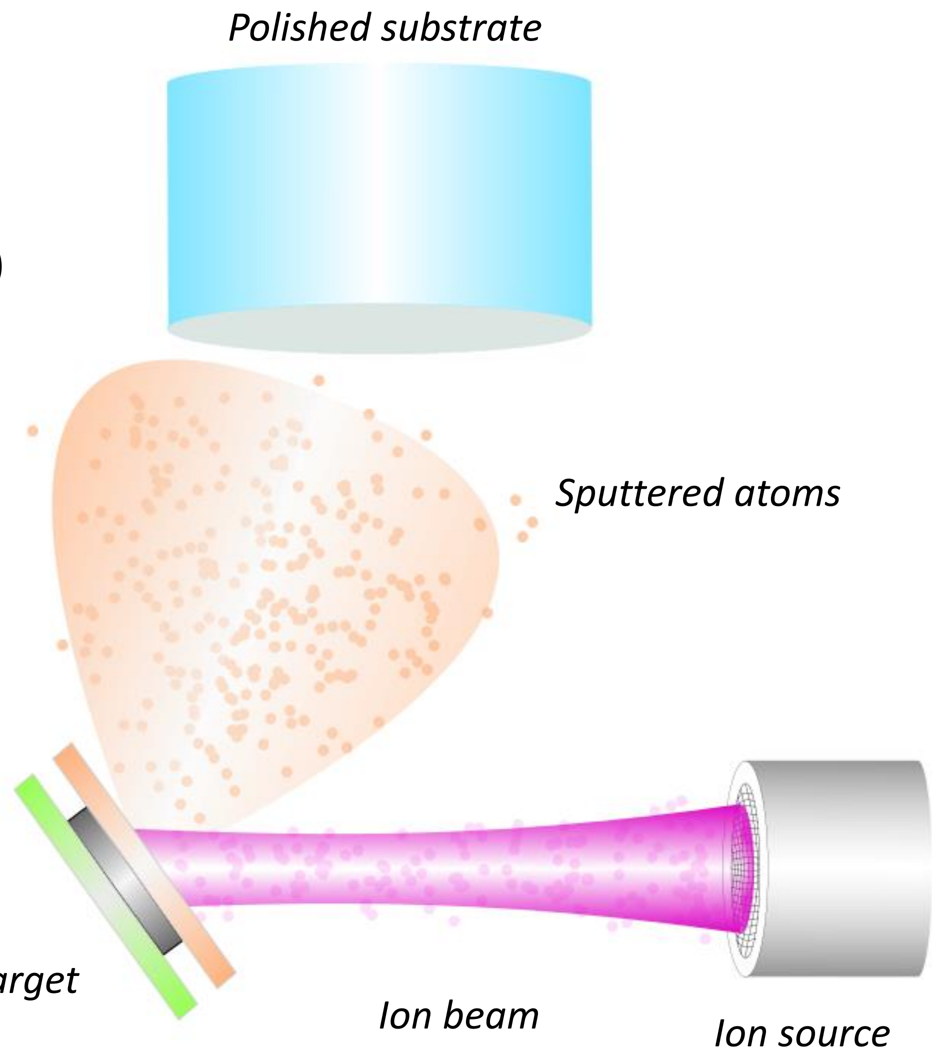


# How to make the « HR coating » ?

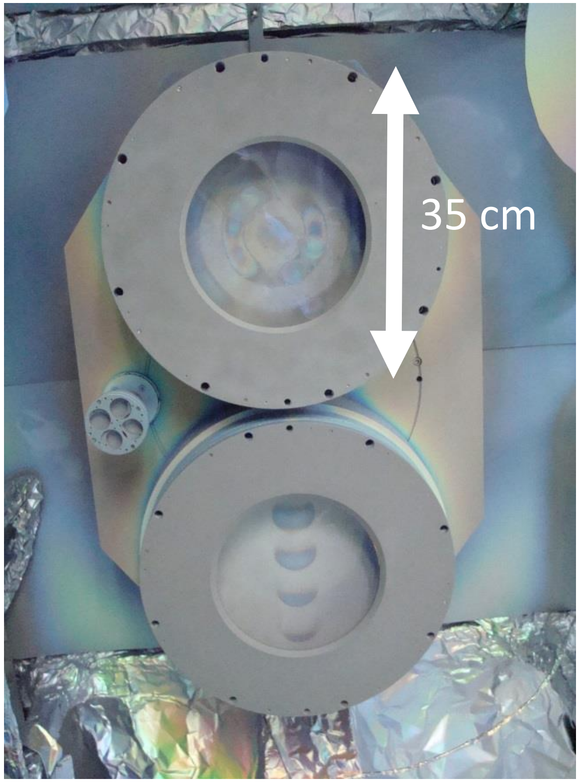
Ion Beam Sputtering (IBS)

- High vacuum
  (base pressure ~$10^{-7}$ torr)
- Energetic deposition
- High density
- Low scattering
- Low absorption



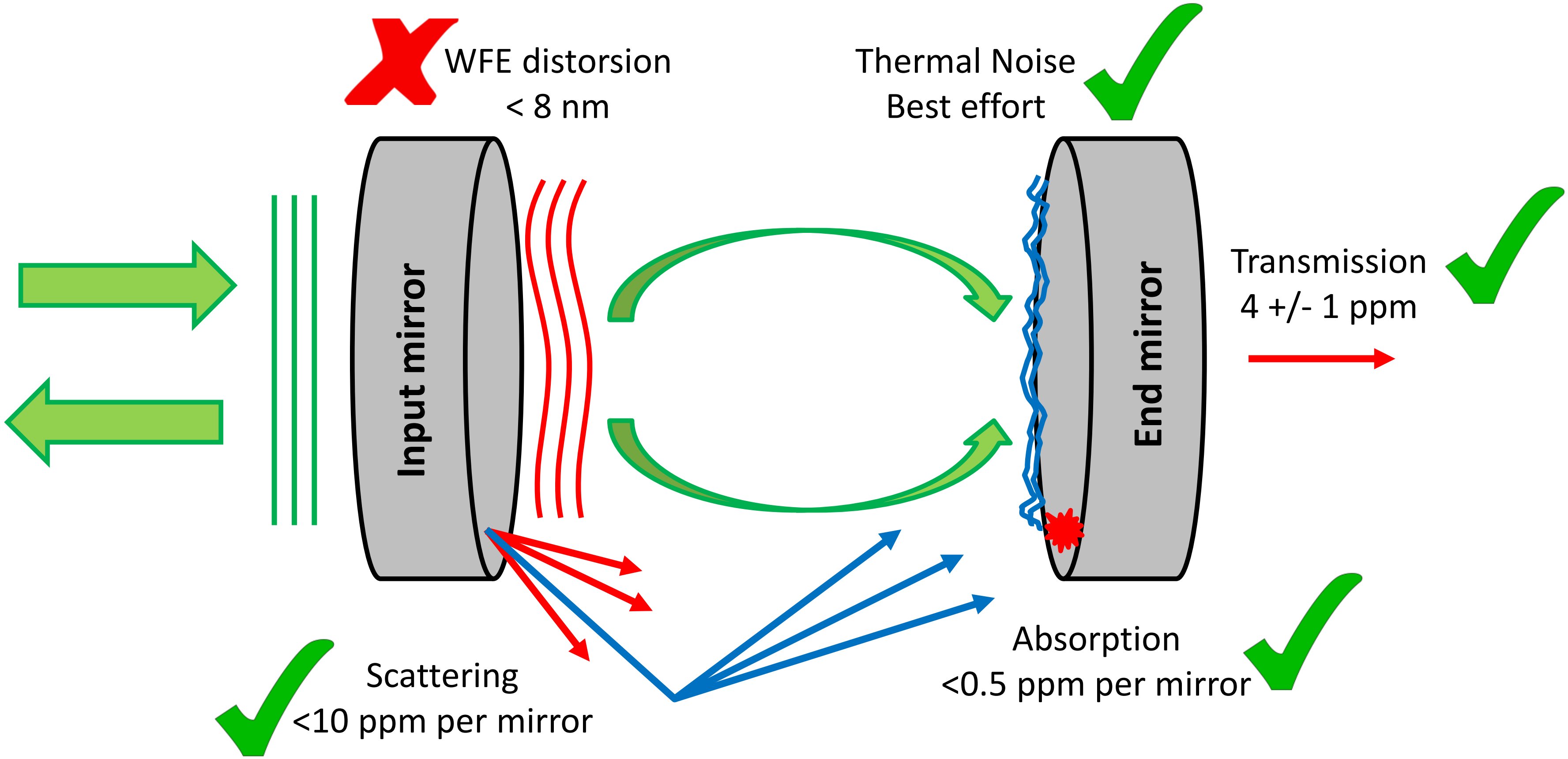

High optical quality

# An home made machine

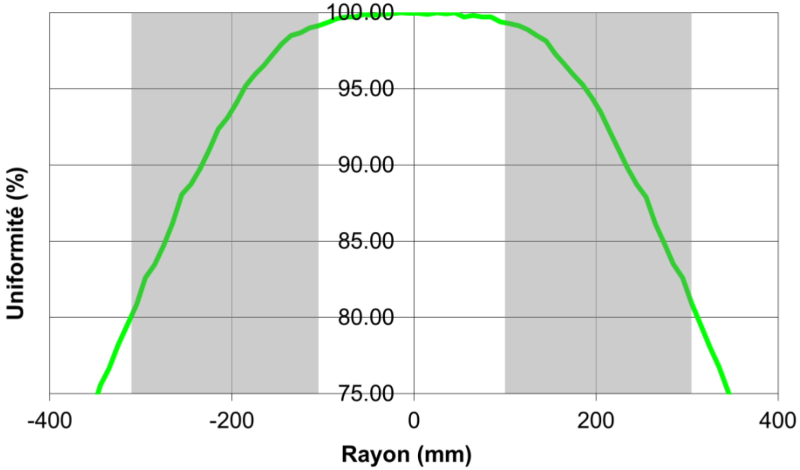

- 10 $m^3$ vacuum chamber
- Able to coat up to Ø1m or 2 Virgo mirrors at a time
- Install in a ISO3 cleanroom

# Requirements




IBS technique allows to produce low-loss coating.

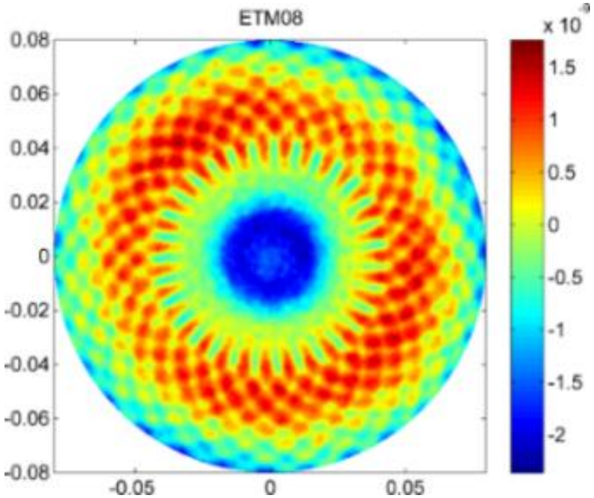
# WFE improvement




Quite large thickness variation

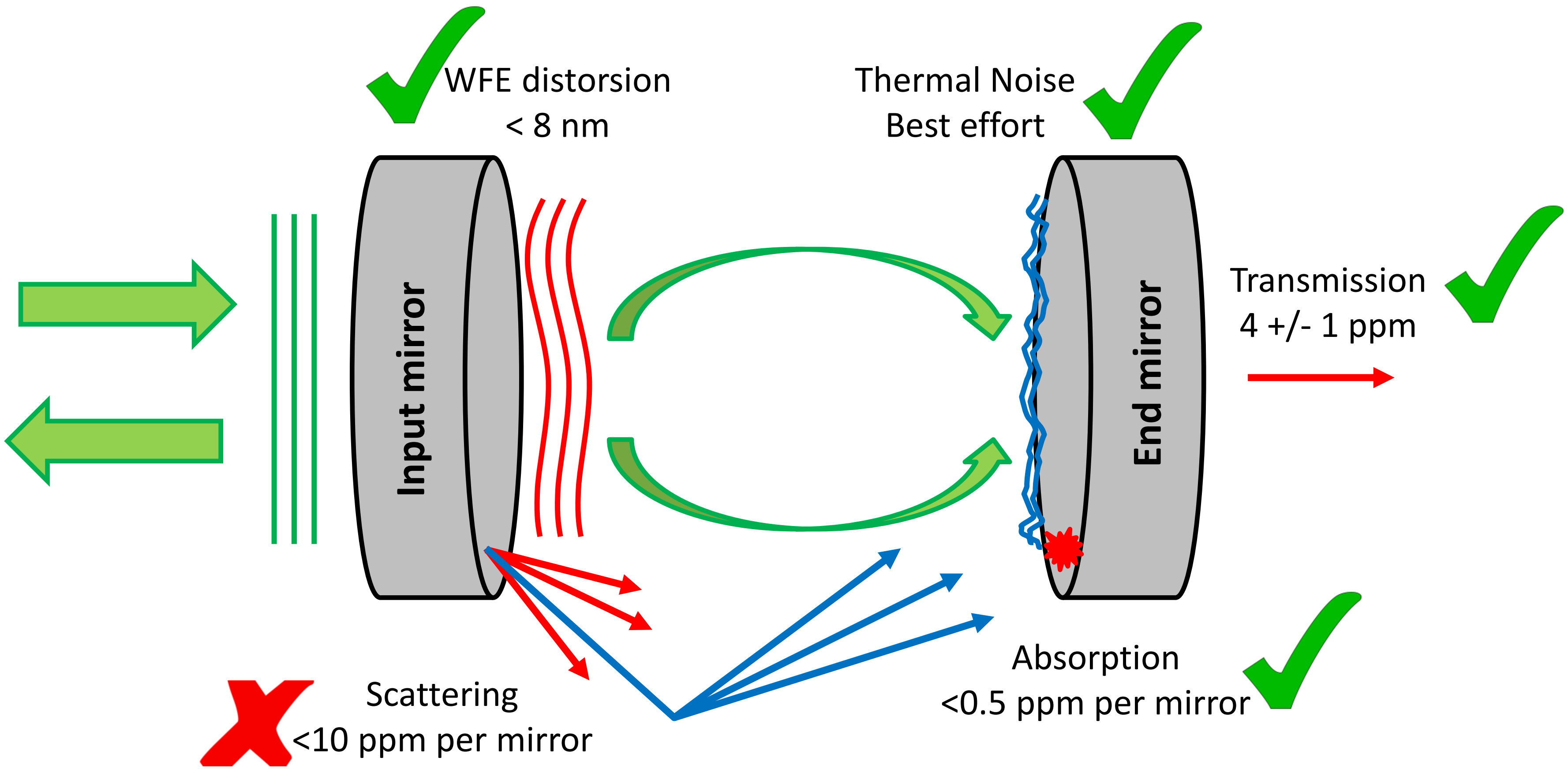
- Strong impact on the optical properties
- Large WFE

20 % → 0.075%

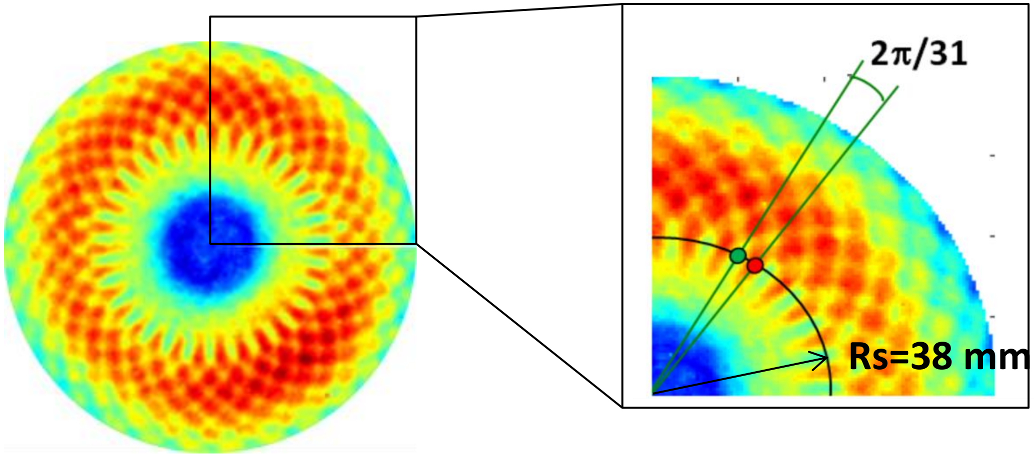

WFE in reflection over Ø160mm (nm)

# Requirements

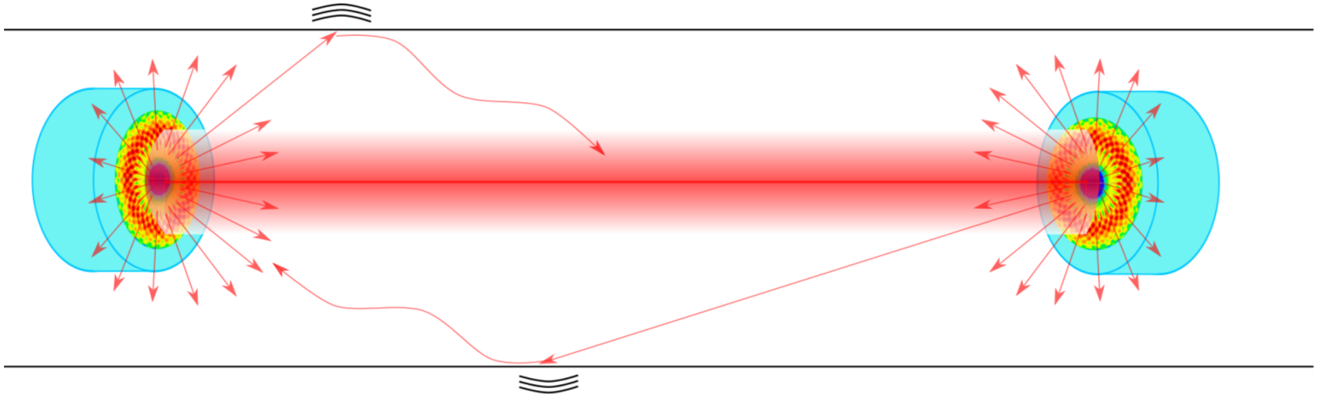



What's happened ?

# The spiral pattern

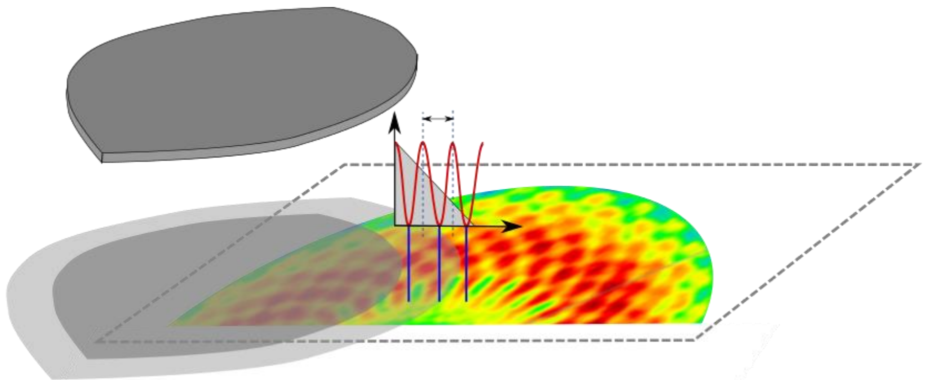


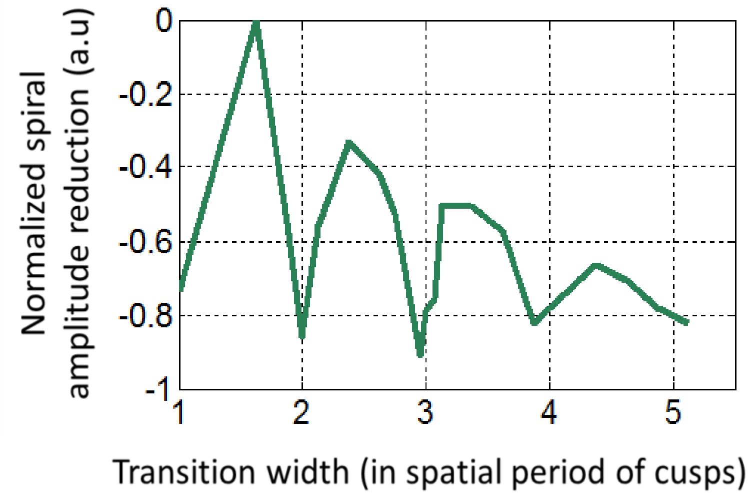

- Maximal spiral amplitude on radius Rs = 38 mm and angular period of $2\pi/31$
- Generated by the combination of the planetary motion and the shadowing mask
- Small defect : only 1.5 nm for a 6 µm coating total thickness



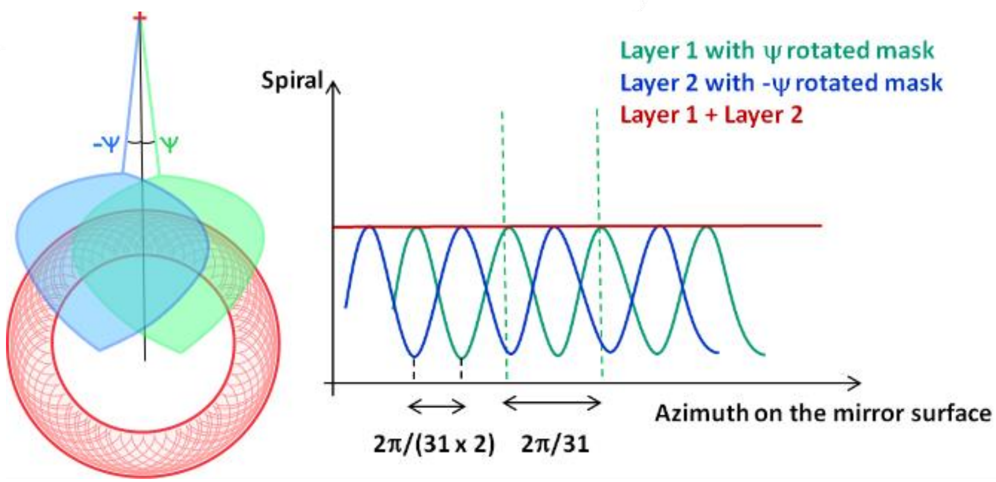
BUT this tiny defect limits the sensitivity of the GW detectors

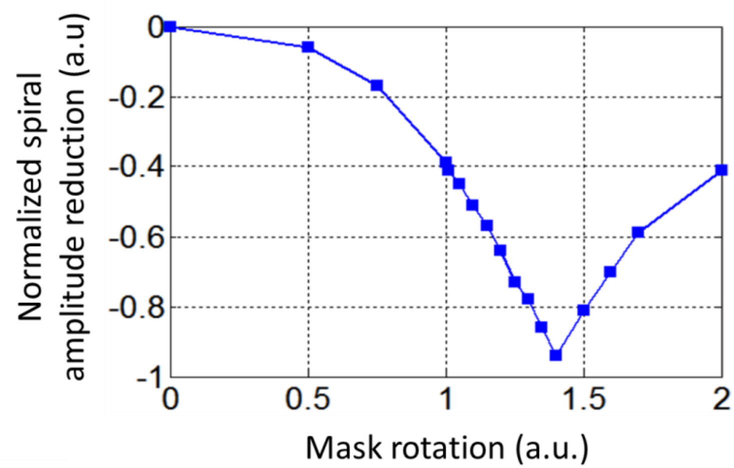
## The « blurring » technique





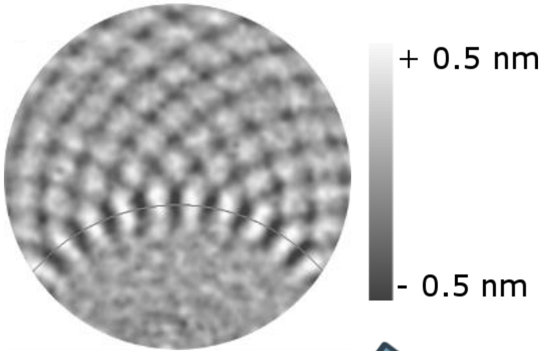

## The « interference » technique



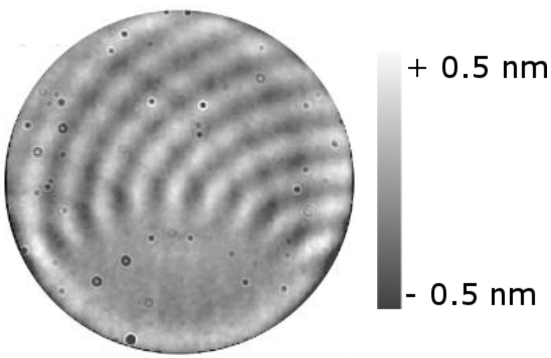
# Final results

Before mitigation



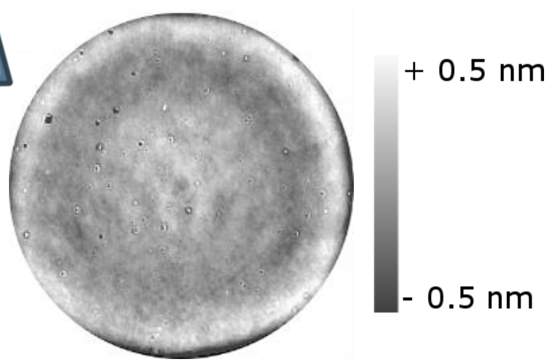

x 1/2

With the blurring technique

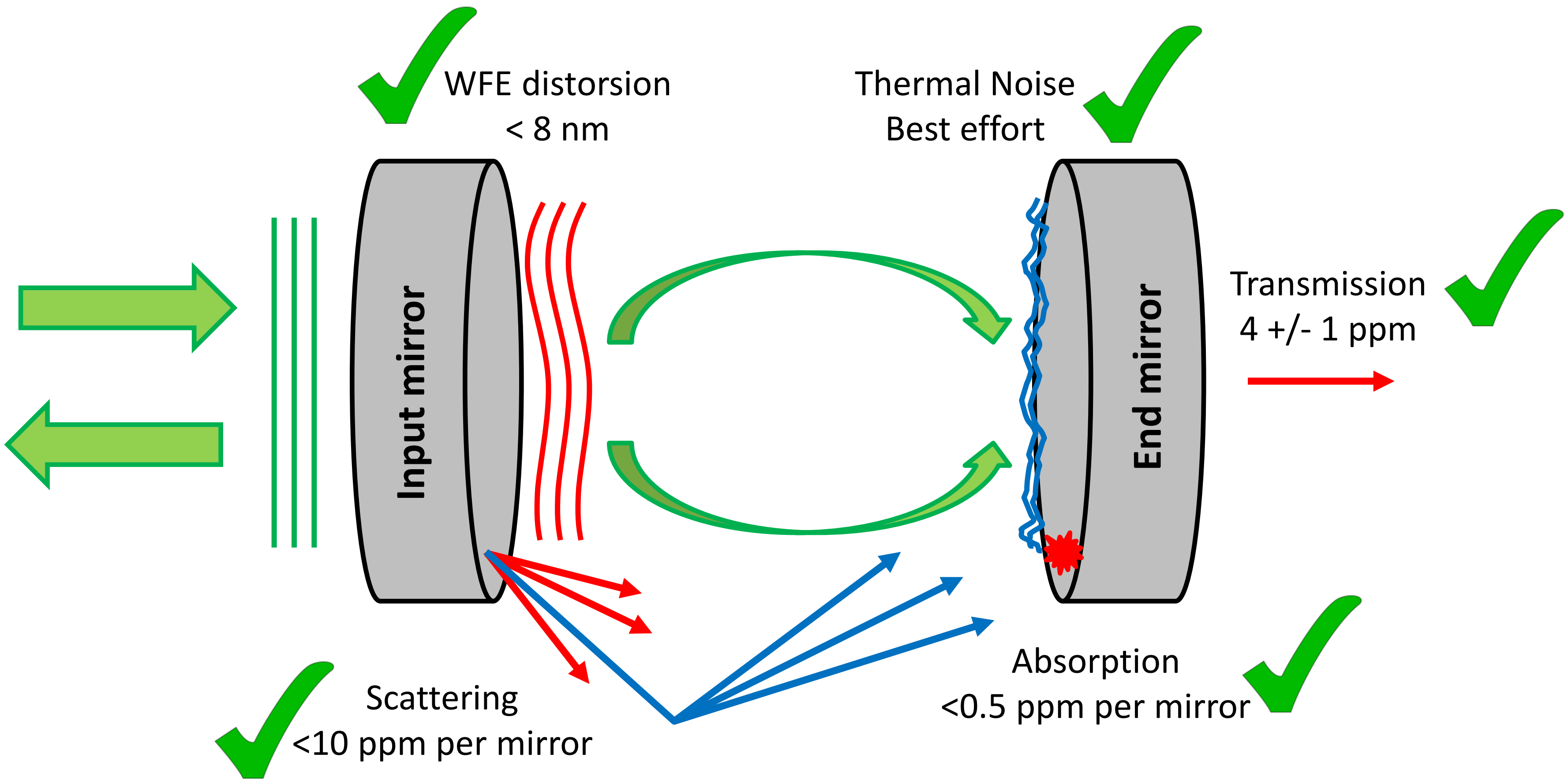



x 1/3

With the blurring and the interference technique



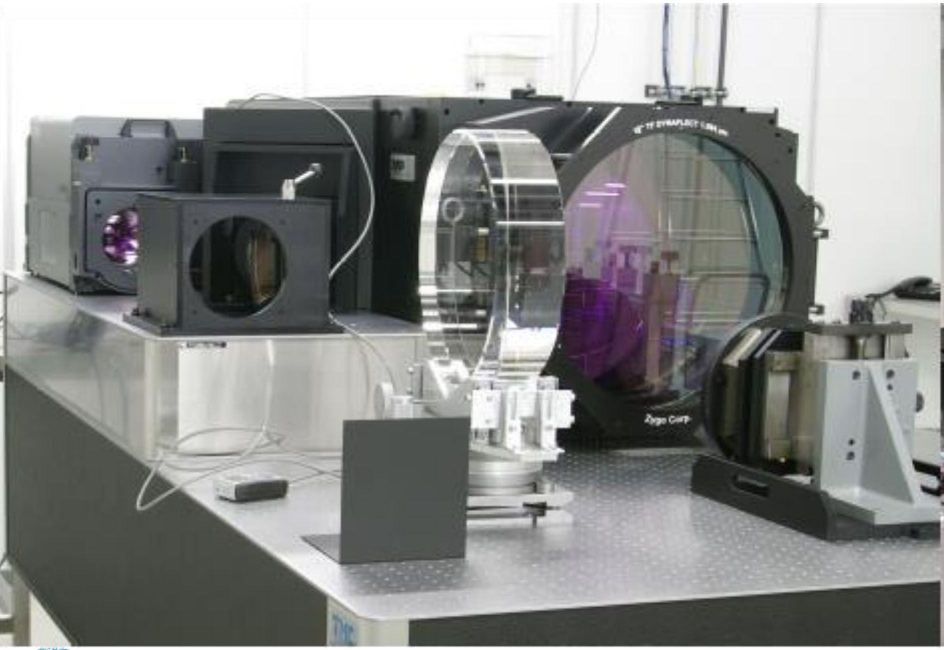
# Requirements

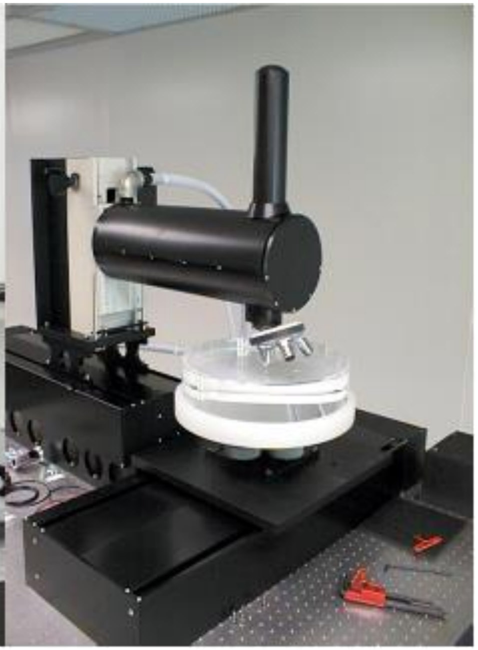


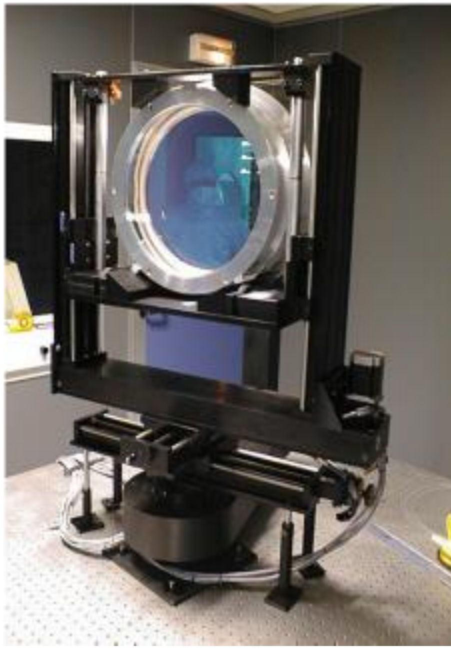
# Complete optical metrology

Essential step in order to check the actual performances of the optics :

- Transmission
- Optical absorption
- Waveront error (WFE)
- Microroughness
- Scattering

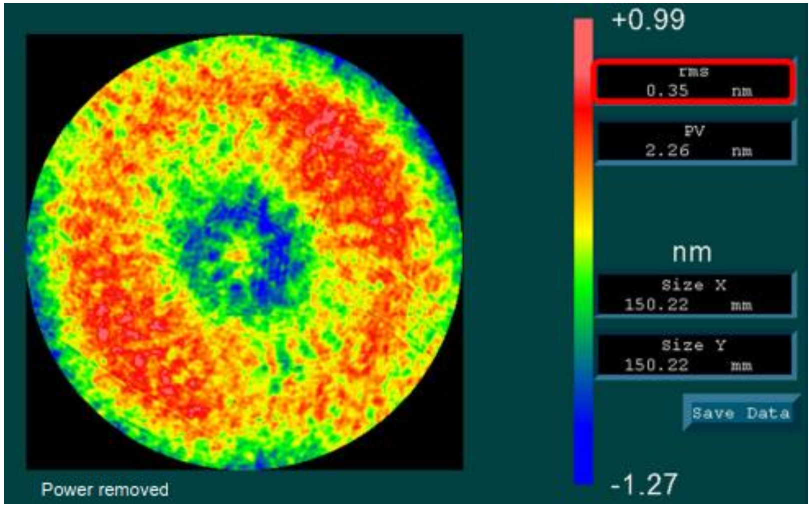




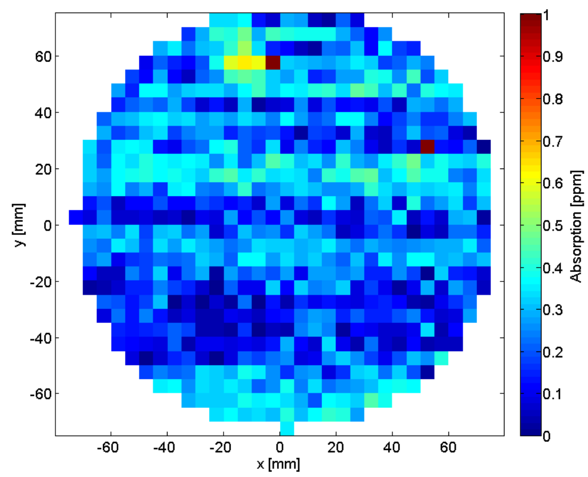


# Final performances @ 1064 nm

- Flatness : 0.35 nm RMS (w/o curvature)
- Transmission matching : difference <0.002%
- End mirror transmission 4 ppm

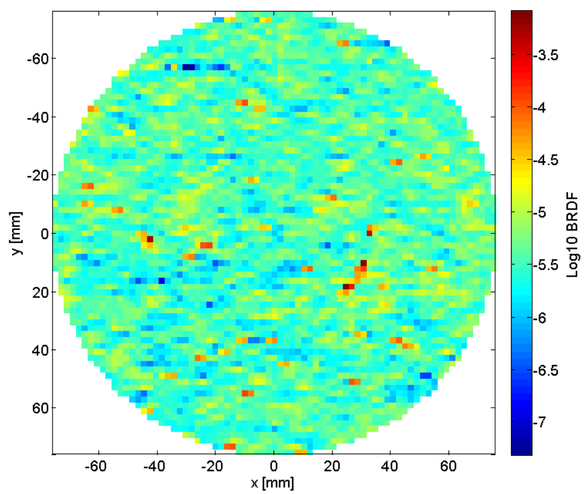



Absorption



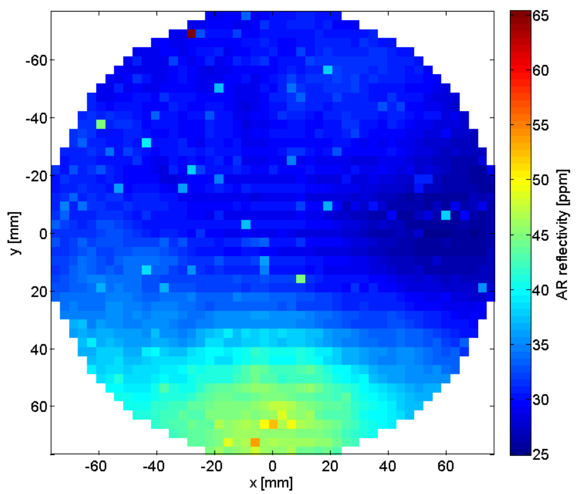

0.2 ppm

Scattering



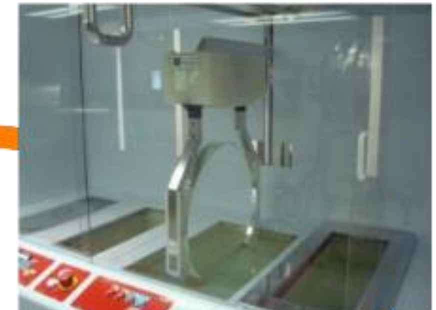

4 ppm

AR reflectivity

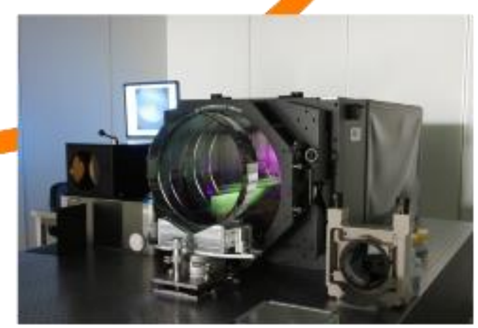



30 ppm

# Some numbers



- 10 years R&D on the materials
- 4 years R&D on the uniformity
- 24 substrates of 40 kg coated
- 480 h of coating (including 15 nights)
- 0.1 mm total thickness coating
- 240 days of metrology



# Thank you

# Interferometric measurements