Symposium OCLA 2017

The gravitational waves detection: 20 years of research to deliver the LIGO/VIRGO mirrors

Christophe MICHEL on behalf of LMA Team

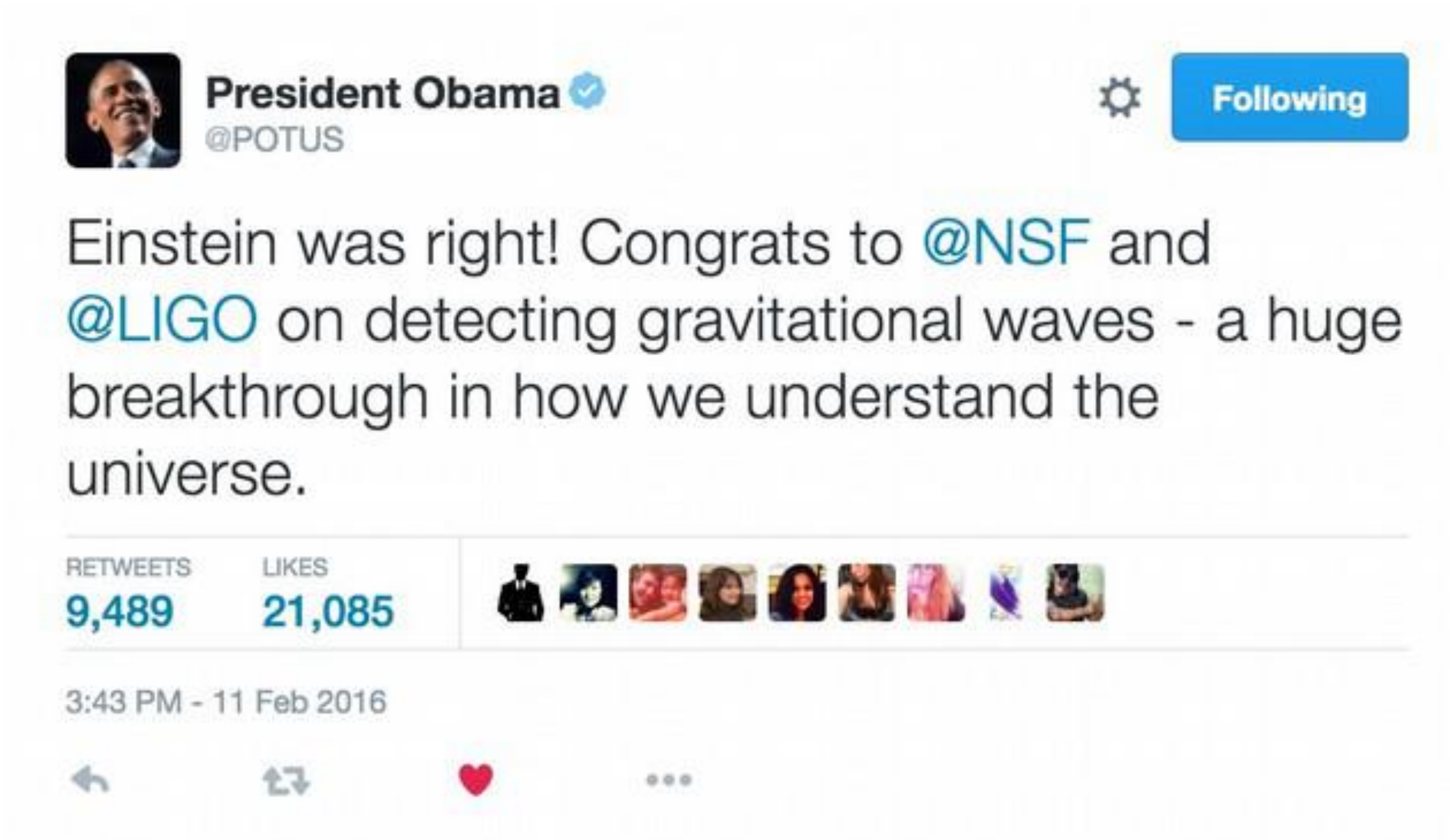
The event

- February 11th 2016 LIGO and VIRGO announced the first direct detection of gravitational waves

- https://www.youtube.com/watch?v=vd1Pak5f6GQ

- http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

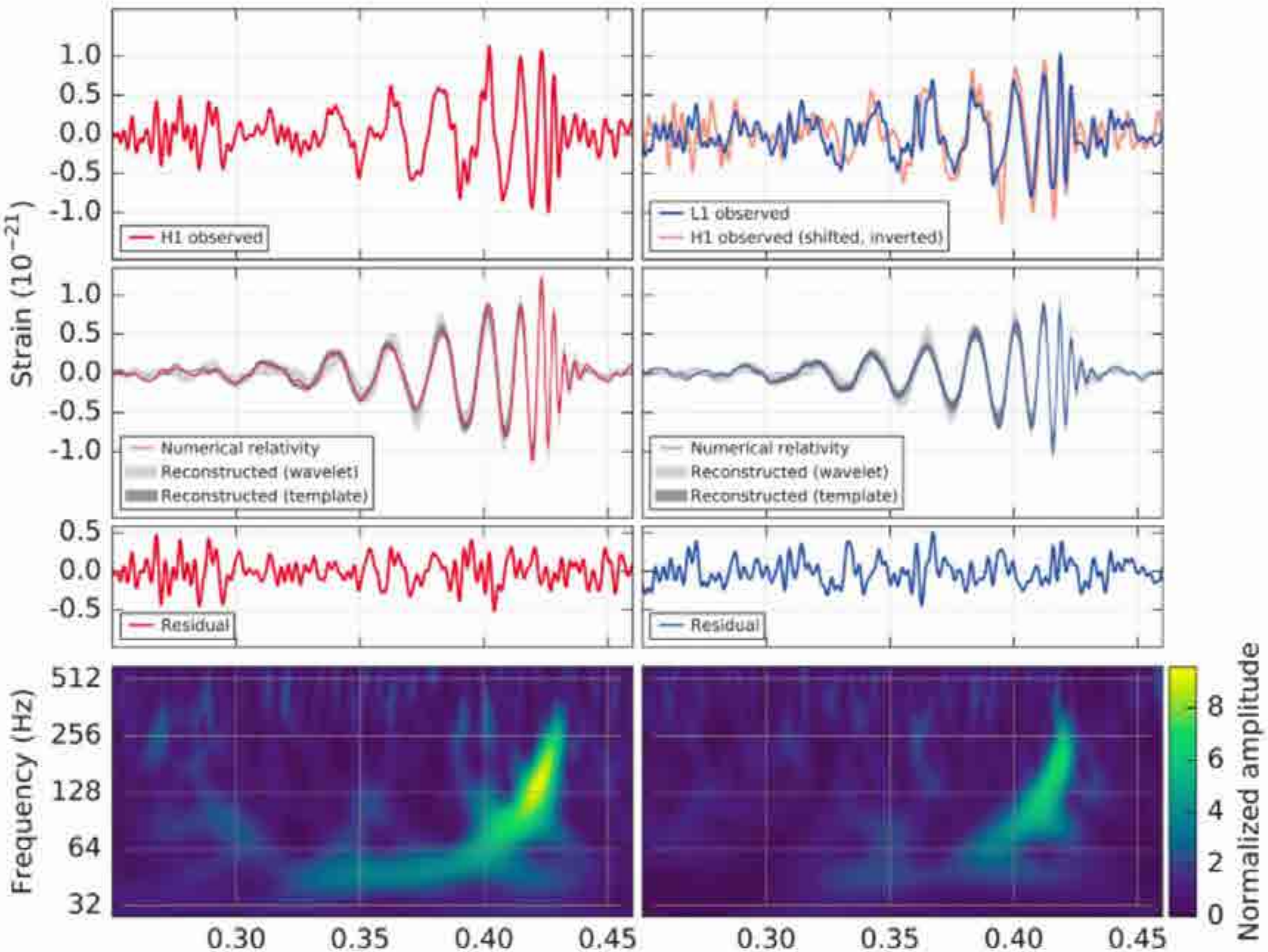
The event


President Obama
@POTUS
Following
Einstein was right! Congrats to @NSF and @LIGO on detecting gravitational waves - a huge breakthrough in how we understand the universe.
RETWEETS
9,489
LIKES
21,085
3:43 PM - 11 Feb 2016

The event

- Origin: binary black hole merger
  - ≈ 34 Msun & ≈ 29 Msun
  - 1.3 billion years
- General relativity theory validated a century after Einstein's prediction
- A new way for astrophysics to explore the universe
- What has been really measured?
  - $\Delta L/L=10^{-19}$

The event



Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude

The event

Gravitational Waves detectors: Special Michelson interferometers

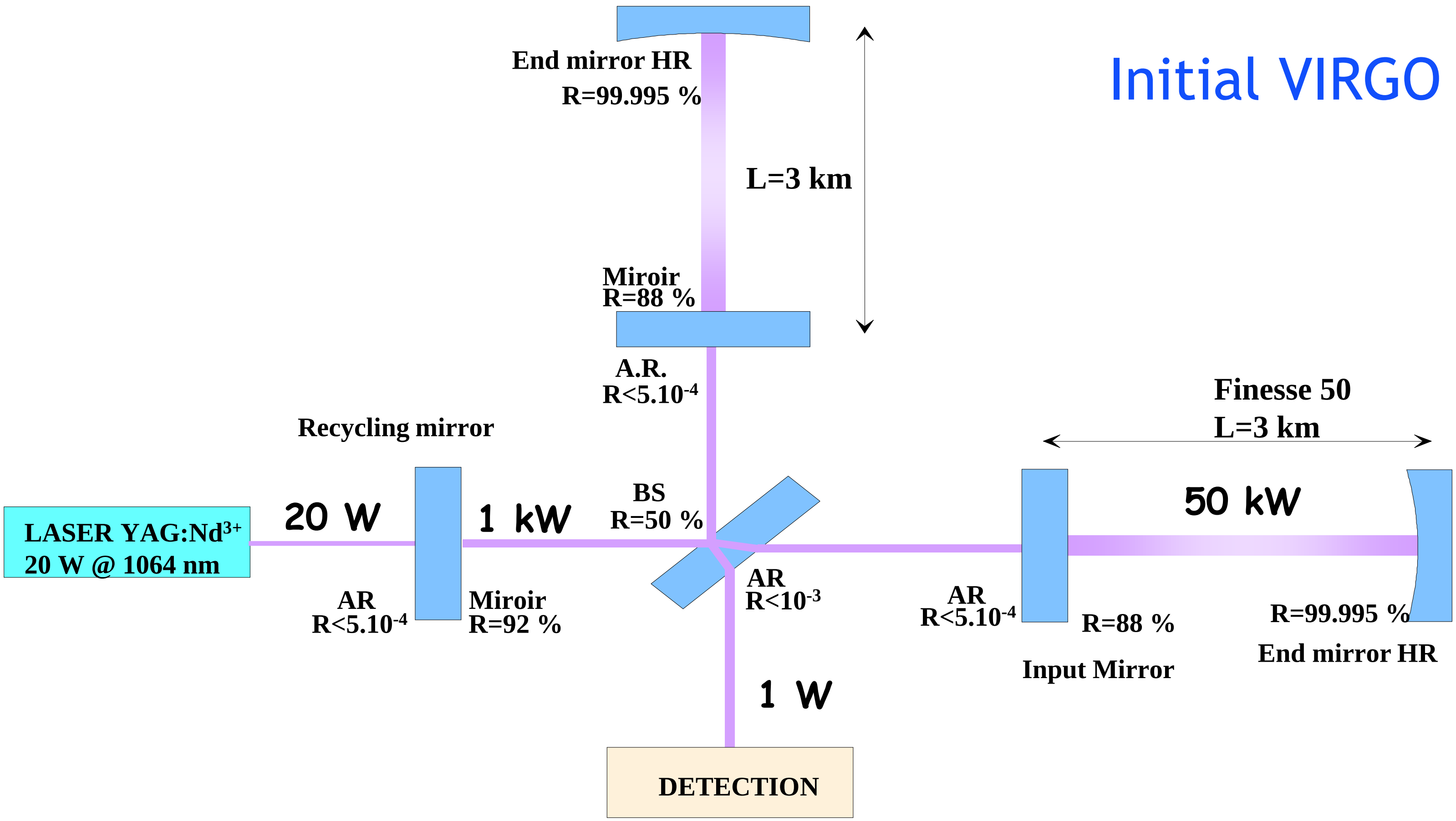
Laser_interferometer2.mp4

SUMMARY

1. ## The optics requirements:
    1. Optics requirements
    2. State of the Art in 1992

2. ## The first generation: The way to large optics
    1. The large IBS coating chamber
    2. The metrology associated
    3. The new facilities: LMA-VIRGO building, cleaning, annealing, handling
    4. Results
3. ## The second generation
    1. Low mechanical losses hunting
    2. Uniformity improvements
    3. Results
4. ## The future: towards the third generation

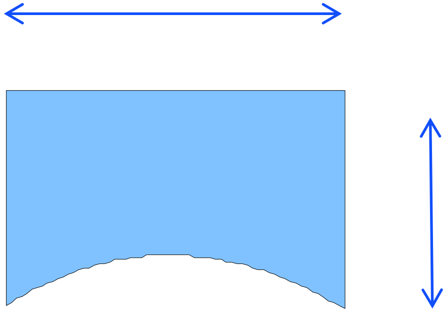
1.1 Optics requirements



1.1 Optics requirements

Physical dimensions:

Ø =350 mm



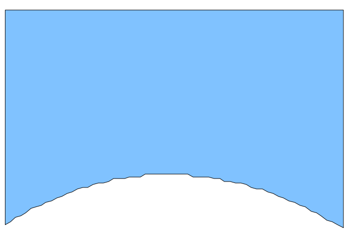
e =100 mm

Material :Pure fused silica

Weight: 20 kg

1.1 Optics requirements

Optical requirements:



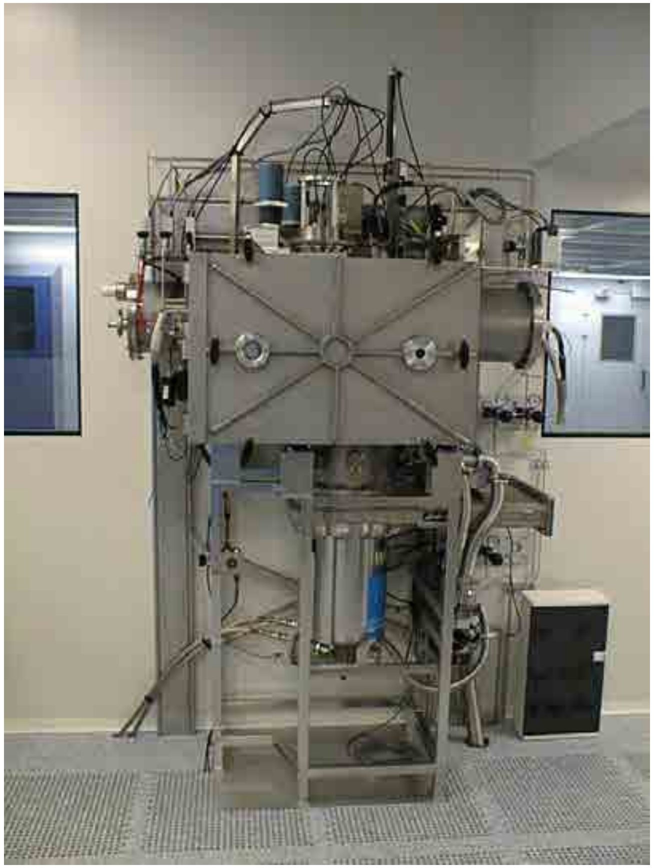
A< 1 ppm on Ø150 mm

S<10 ppm on Ø150 mm

Wavefront < 8 nm rms on Ø150 mm

1.2 State of the art in 1992

- LMA started IBS coatings in 1986
- Home made IBS coater
- 10 m^2 Clean Room ISO 3
- 12 cm Filament Kaufman Ion Source
- Capabilities: planetary 3 *Ø 2 inches
- Uniformity: 1 % on Ø 2 inches

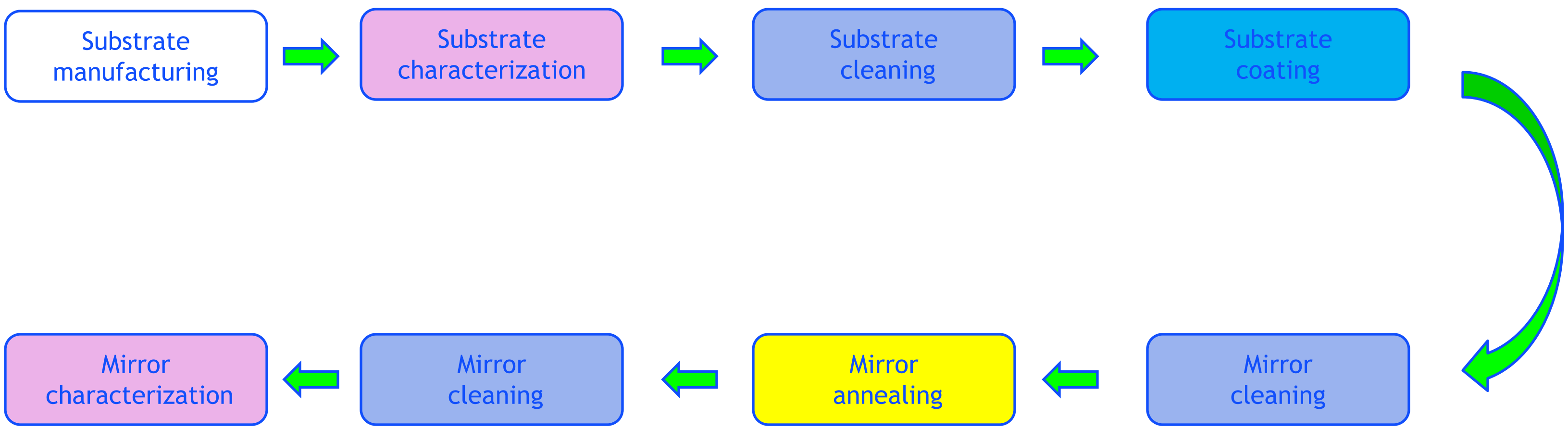


1.2 State of the art in 1992

- Low losses for gyrolaser
- Metrology @ 633 nm
- A< 5 ppm @ 663 nm; S< 10 ppm @ 633 nm
- First gyrolaser used by Ariane 4 equiped by mirrors made at LMA (june 1989)

2. The first generation: The way to large optics

- Beginning of 90's: contact with VIRGO Project
- 1992: official start of VIRGO
- Main challenges: adapt the mirror cycle to large optics



- Begining of 90's: contact with VIRGO Project
- 1992: official start of VIRGO
- Main challenges: adapt the mirror cycle
  - ◆ Large optics: Ø 50 mm to Ø 350 mm; 6 mm to 100 mm thick
    - » New coating chamber; new cleaning machine, new oven
  - ◆ Heavy optics: 0.03 kg to 20 kg
    - » New handling tools
  - ◆ Low losses @ 1064 nm on Ø 150 mm
    - » New optical metrology benches allowed mapping of full area
  - ◆ Uniformity on Ø 150 mm

- Specifications:
  - Coating substrate up to Ø 1 m , 500 kg
  - Uniformity: 1 % on Ø 150 mm in single rotation without mask or 1% on 2 Ø 350 mm in planetary with masks
  - Low optical losses
- Design:
  - Development of a simulation tool to calculate the geometry :
    Ion source – Target- Substrate
  - 5 years (1992-1997)
- Reliability and future evolution :
  - Use of standard component (cryopump, valves, ion source, XTC controller….)
  - Home made software
  - Conctruction and commissioning: 3 years (1998-2000)

GC view from rear side

- ☞ Ion Beam sputtering technoloy
- ☞ Budget: 2 M€
- ☞ Size: 2.2 x 2.2 x 2 m^3
- ☞ Pumping system: 2 dry pumps
  4 cryopumps
- ☞ Pressure: 1.10^{-7} mbar in 3 hours
- ☞ 16 cm RF Ion source + RF Neutralizer
- ☞ Thickness monitoring: 4 XTC

2. 1 The large IBS coating chamber

GC view from clean room ISO 3

- 2 multi targets:
- Ta2O5/silica layers
- 2 substrate holder:
  - single rotation/planetary motion
  - corrective coating robot
- deposition speed: 0.1 à 3 Å/s
- capability: up to Ø 1m in single rotation

Coating characterization:
Scattering,transmission,reflexion on Ø 550 mm: *CASI*

Credit: photothèque CNRS- Cyril FRESILLON

Substrate , cleaning process and coating characterization:
µroughness and defect detection on Ø 350 mm : *µmap*

Substrate & Coating characterization
Wavefront on Ø 350 mm @ 1064nm:
Phase Shift 6 inches Interferometer

Substrate & Coating characterization :
Absorption @ 1064 nm on Ø350 mm
Photothermal Deflection System

Credit: photothèque CNRS- Cyril FRESILLON

Coating characterization :
T & R from 175 to 3300 nm
Lambda 1050 Perkin-Elmer spectrophotometer

Renovation of synchrocyclotron building

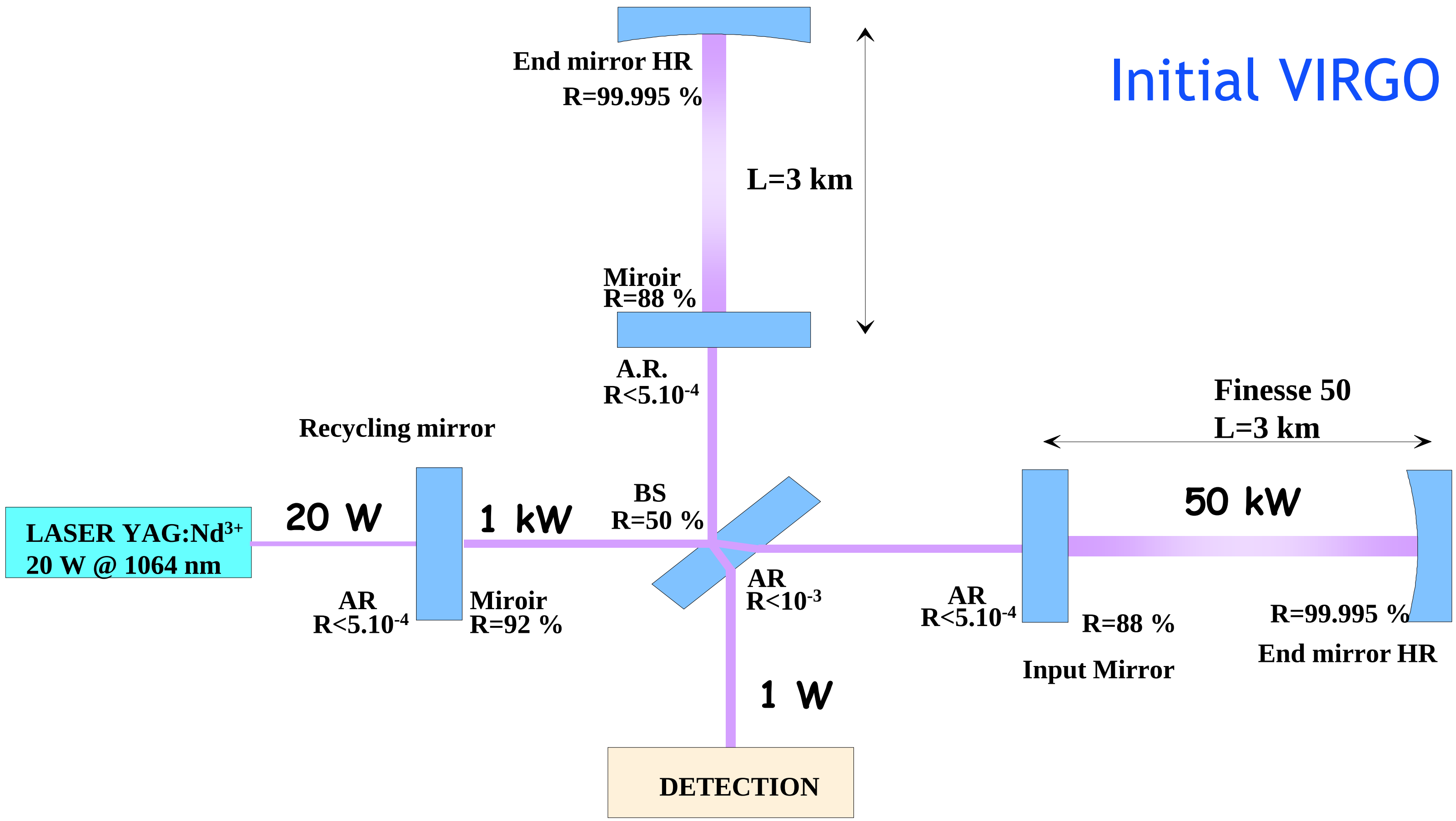
- 3 levels: 2500 m^2
- 500 m^2 clean room with 150 m^2 ISO 3 clean room

Handling requirements:

- Substrate contact area: the barrel
- Put the substrate in metallic mounts:
  - Translation and 180° rotation

Credit: photothèque CNRS- Hubert RAGUET

2002: all the main optics delivered to VIRGO



VIRGO End MIRROR #1

Size: 350 mm * 96 mm

Substrat: Pure fused suprasil silica from Heraeus

Polishing: General Optics

Coating:

Measurements/ requirements

R = 0.99995 / R = 0.99995

Absorption = 0.63 ppm /A < 1 ppm

Scattering = 4 ppm / D < 5 ppm

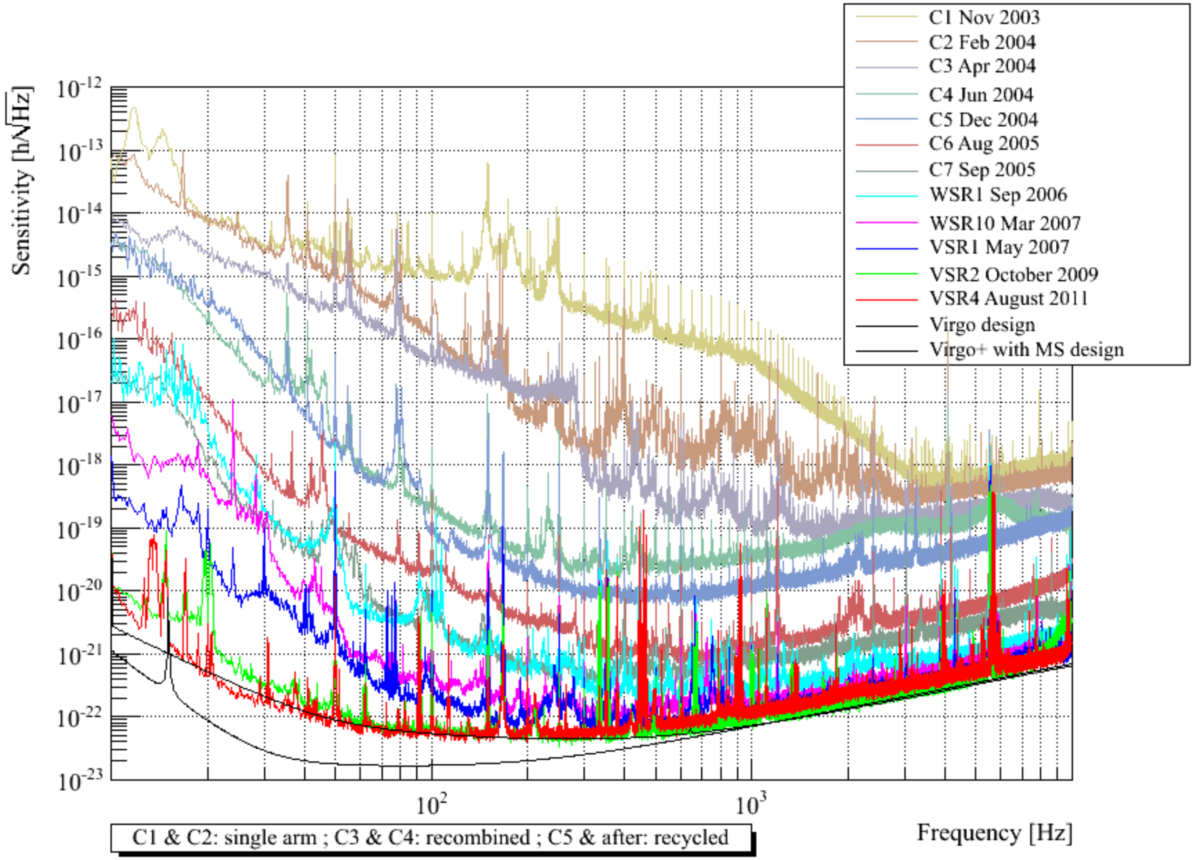
μroughness = 0.5 Å RMS / < 0.5Å

Wavefront= 3.8 nm RMS/< 8 nm

2002 to 2006: commissioning

2007 to 2008: Virgo Scientific Run

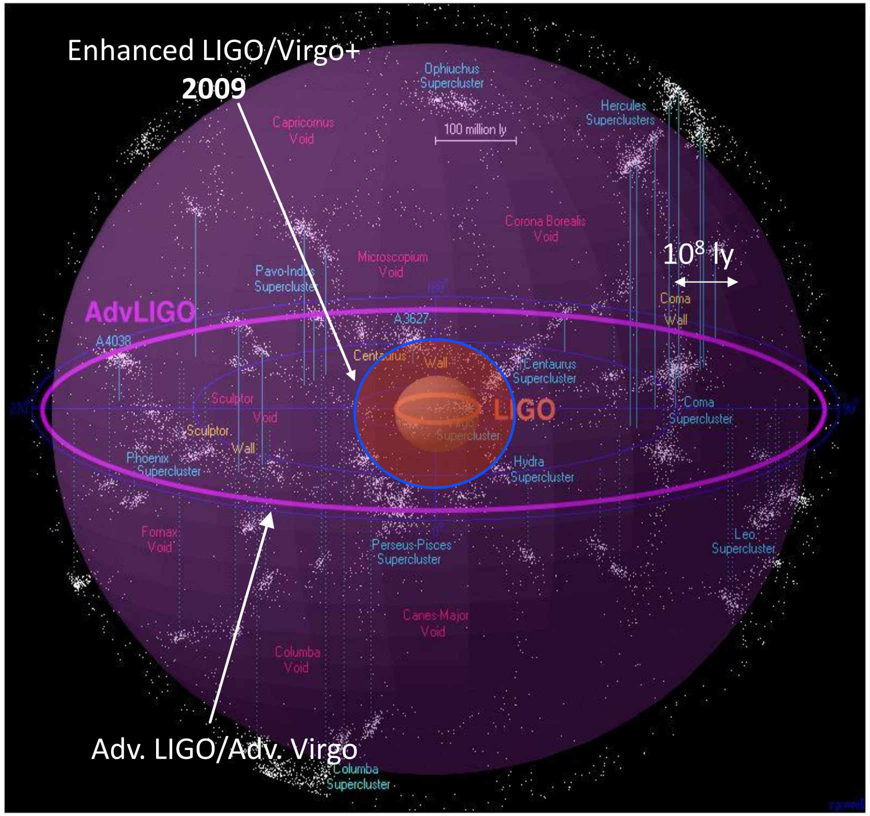
2008 to 2011: VIRGO +



Sensitivity close to design but no detection

2008 :green light for a second generation

3.The second generation

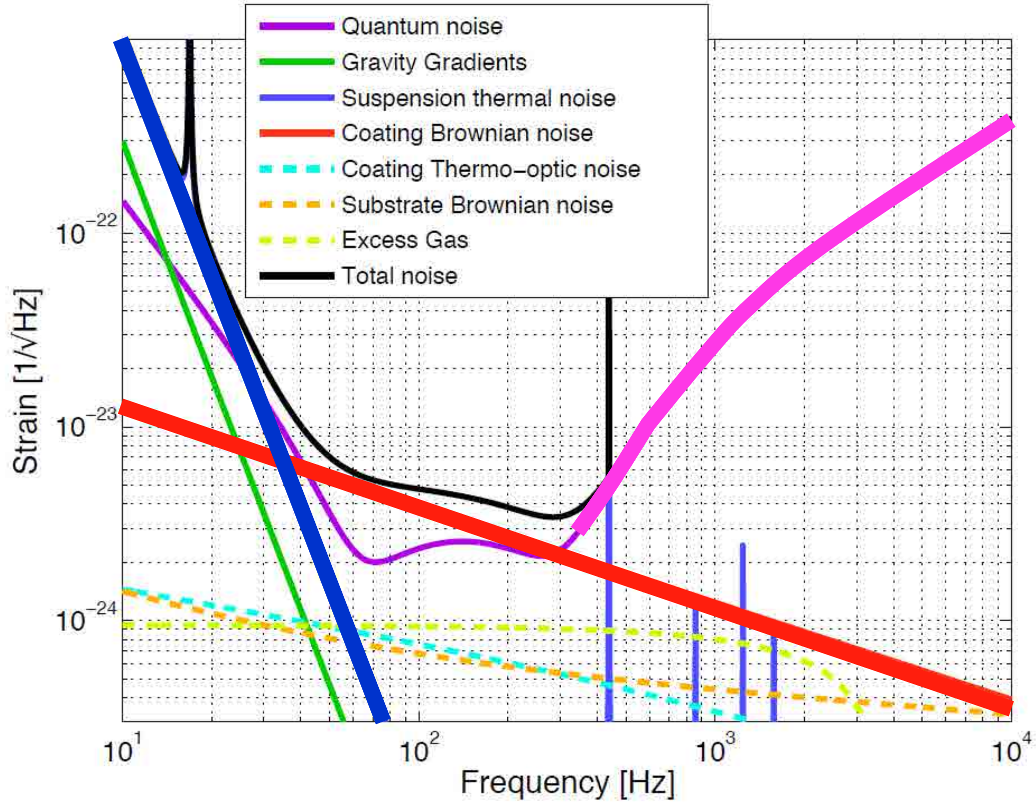


Credit: R.Powell, B.Berger

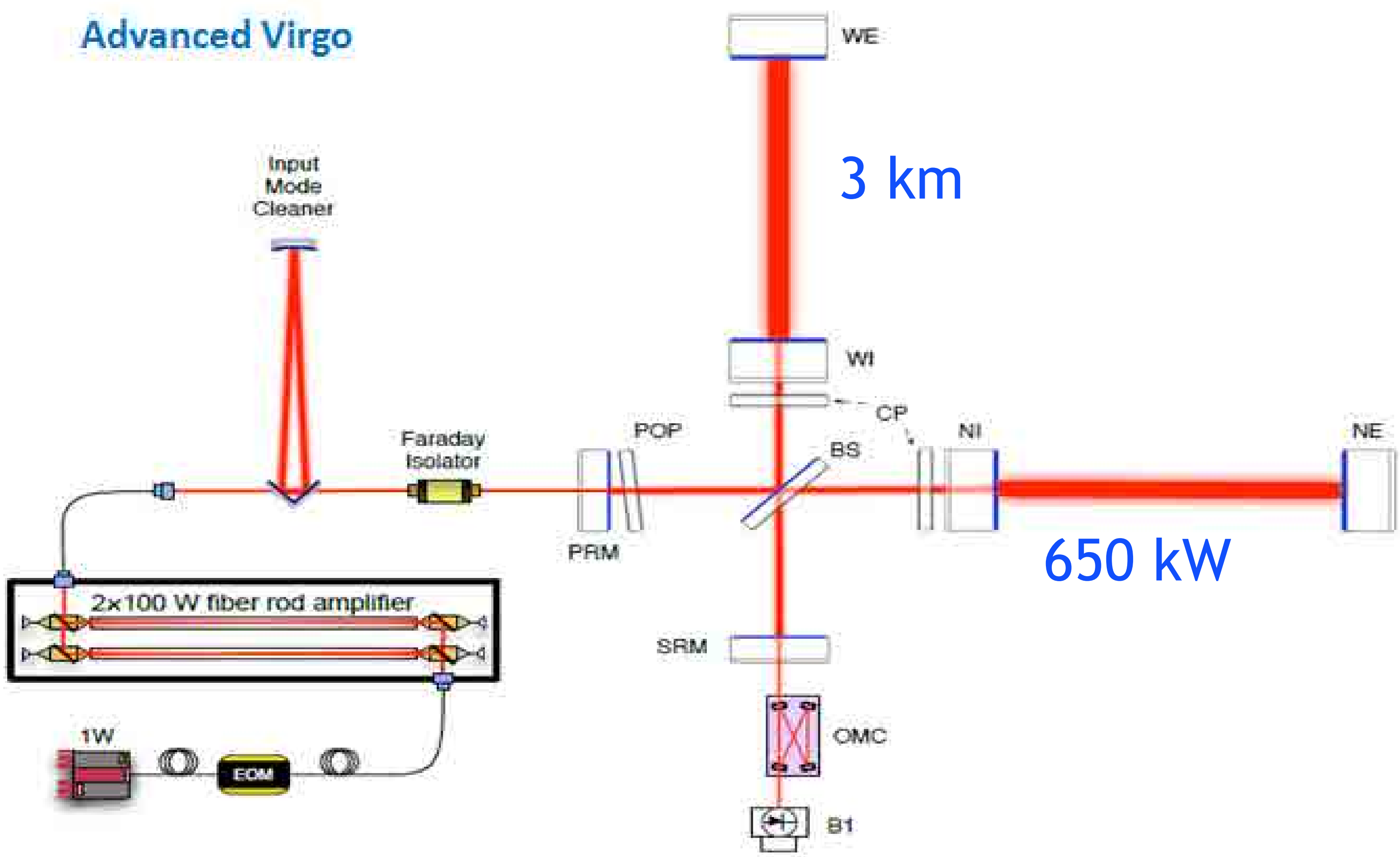
Advanced Virgo: sensitivity * 10, rate * 1000

3.The second generation

- Mirror vs sensitivity
  - Photon noise: optical losses
    - » Absorption
    - » scattering
    - » wavefront
  - Thermal noise
    - » Coatings thermal noise
    - » Mirror size
  - Laser radiation pressure and suspension thermal noise
    - » Mirror weight
- Interferometer stability
  - Thermal effects
    - » Absorption
  - Scattering light
    - » Scattering and wavefront



3.The second generation



AdV. VIRGO

3.The second generation

- Optics are the key elements of the interferometer
- Heavier and thicker optics:
  - Test Mass: Ø 350 mm, 200 mm thick, 40 kg, clear aperture: Ø 16 cm
  - BeamSplitter: Ø 550 mm, 65 mm thick, 40 kg
- RTL: 75 ppm on each arm
- Huge requirements on coatings
  - Low absorption: <0.5 ppm @ 1064 nm
  - Low scattering: < 5 ppm
  - Low thermal noise
  - AR < 100 ppm @ 1064 nm
  - ITM Transmission matching: T(1064 nm)= 1.4% +/- 0.1%
  - 3 bands requirements for R& T: 532, 800 & 1064 nm

3.1 Low thermal noise material hunting

- Thin coatings layers (6 µm) mechanical losses limit the sensitivity in the 50-500 Hz band more than the 200 mm thick substrate due to the associated mirror thermal noise.
  - H: Ta_2O_5 Φ Ta2O5 = 4*10^{-4}
  - L: SiO_2 Φ SiO_2 = 5*10^{-5}

☞Find a new H material with lower mechanical losses

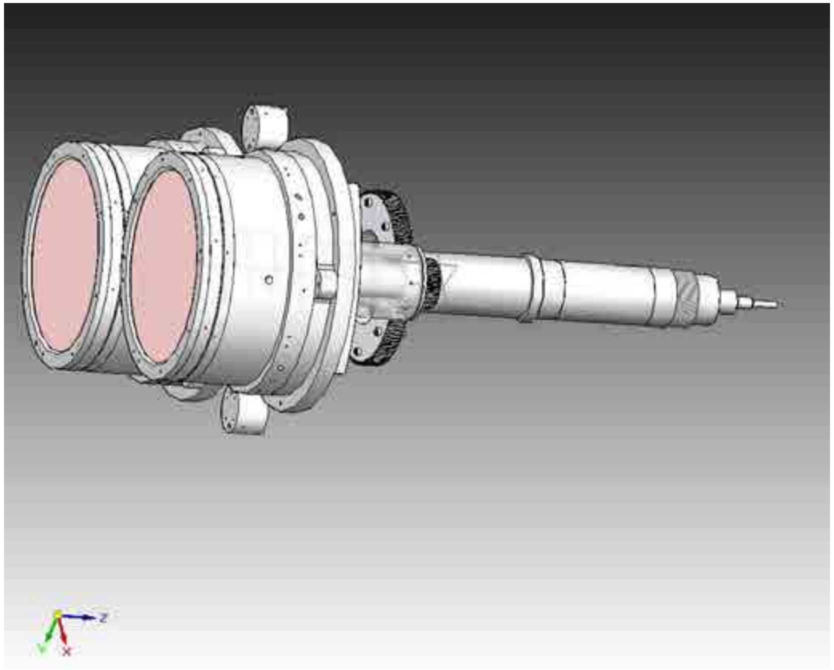
- Development (with Perugia team) of a metrology facility based on cantilevers characterization
- Test many material without improvement.
- Doping tests: best results with Titania doped Ta2O5 F5

3.1 Low thermal noise material hunting

- Work on process parameters: Ti-Ta_2O_5 F5**
- Φ Ti-Ta2O5 F5** = 2*10^{-4}
  - n Ti-Ta2O5 > n Ta2O5 reduced (HL) stack number
  - k Ti-Ta2O5 < k Ta2O5 reduced absorption (A=0.3 ppm @ 1064 nm for HR stack)
- Optimized coating: reduce H in the stack, compensated by L (lower mechanical losses)
- After 6 years LIGO choose Ti-Ta_2O_5 F5** for H with an optimized stack design for the Test Masses coatings
- A study of coating mechanical and optical losses in view of reducing mirror thermal noise in gravitational wave detectors Classical and quantum gravity

3.2 Uniformity improvements

- Second challenge: a better wavefront
- Third challenge: ITM transmission matching: ΔT< 0.014%
  - ☞ 2 test masses coated by batch:
    - ◆ Developpement of a planetary system able to coat 2 substrates Ø 350 * 200 mm



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- Second challenge: a better wavefront
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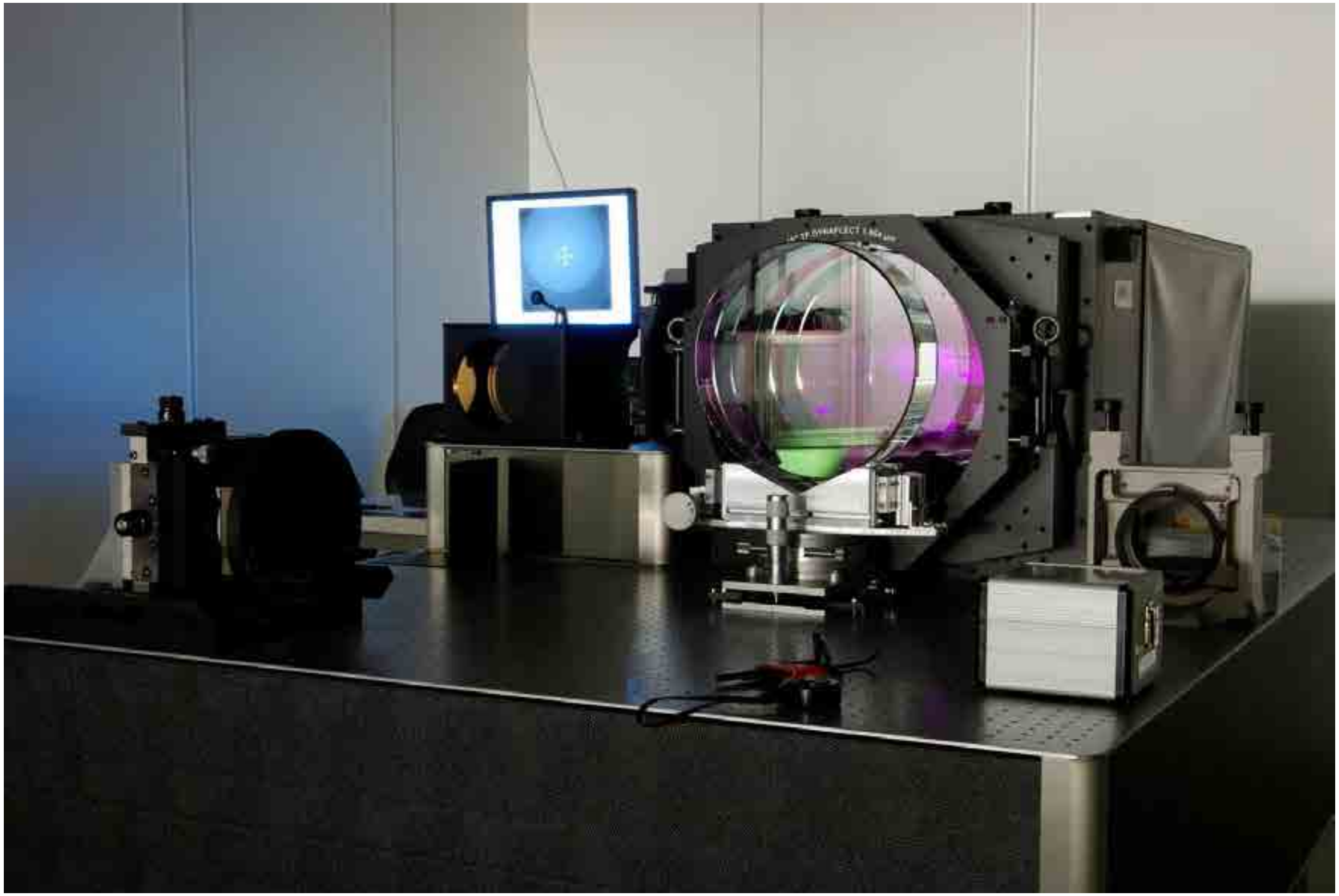
  - ☞ 2 test masses coated by batch:
    - ◆ Developpement of a planetary system able to coat 2 substrates Ø 350 * 200 mm
    - ◆ ZYGO wavelength shifting interferometer with a 18" beam expander (**1064 nm**), pupil diameter 450 mm: measurement of surface flatness below **0.5 nm RMS**

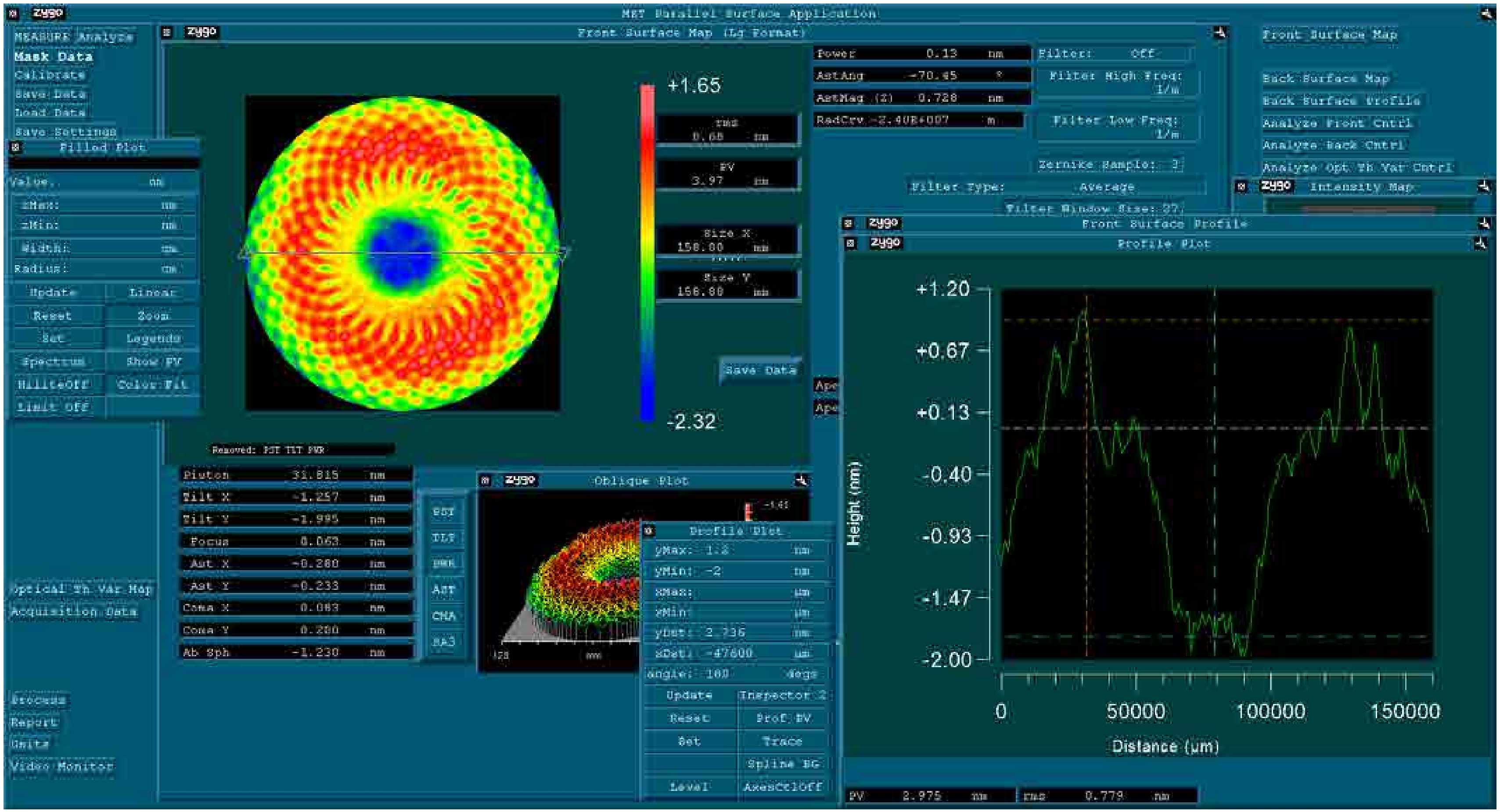
3.2 Uniformity improvements



3.2 Uniformity improvements

- Uniformity requirement: 0.1 % on Ø 160 mm
- 1st Mask shape calculated by simulation then tested then mask shape optimization by iteration
- Need to adapt the metrology process for better accuracy and reliability: spectrophotometry, reflectometry, wavefront
- Test on large thin disk (sample size, material effect with small substrate)

3.2 Uniformity improvements



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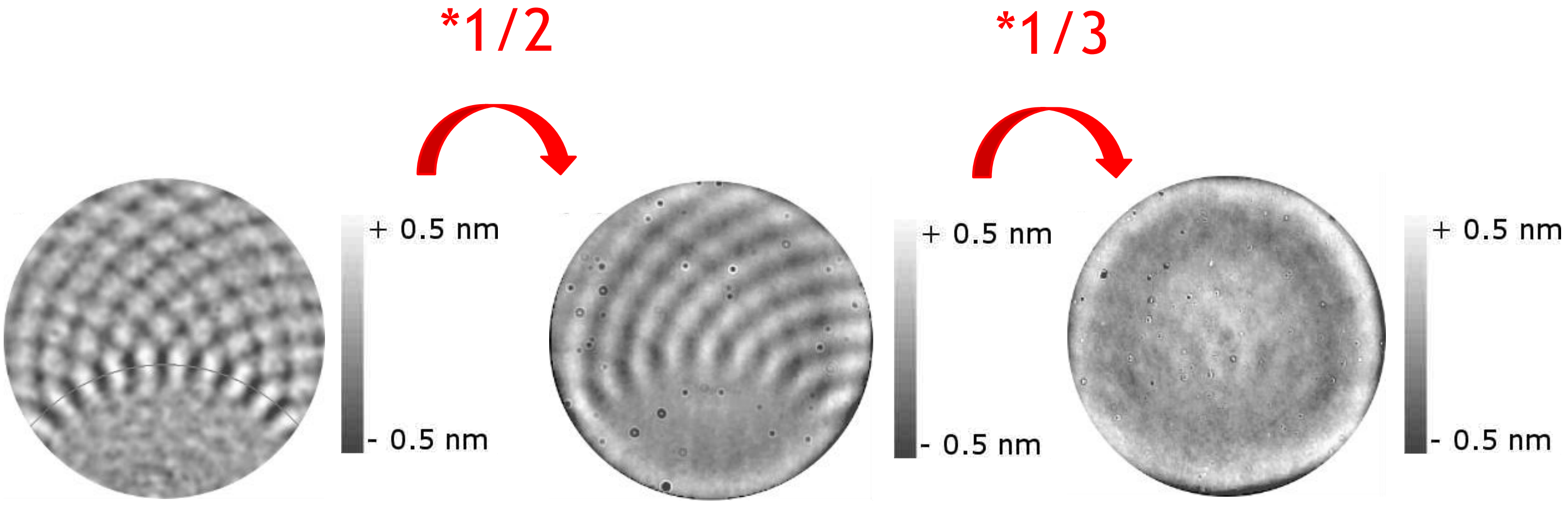
- Test on large thin disk (sample size, material effect with small substrate)
- Combination of planetary motion & mask:
  - spiral pattern (as predicted)
  - 1.6 nm PV on 6000 nm ☞ scattering

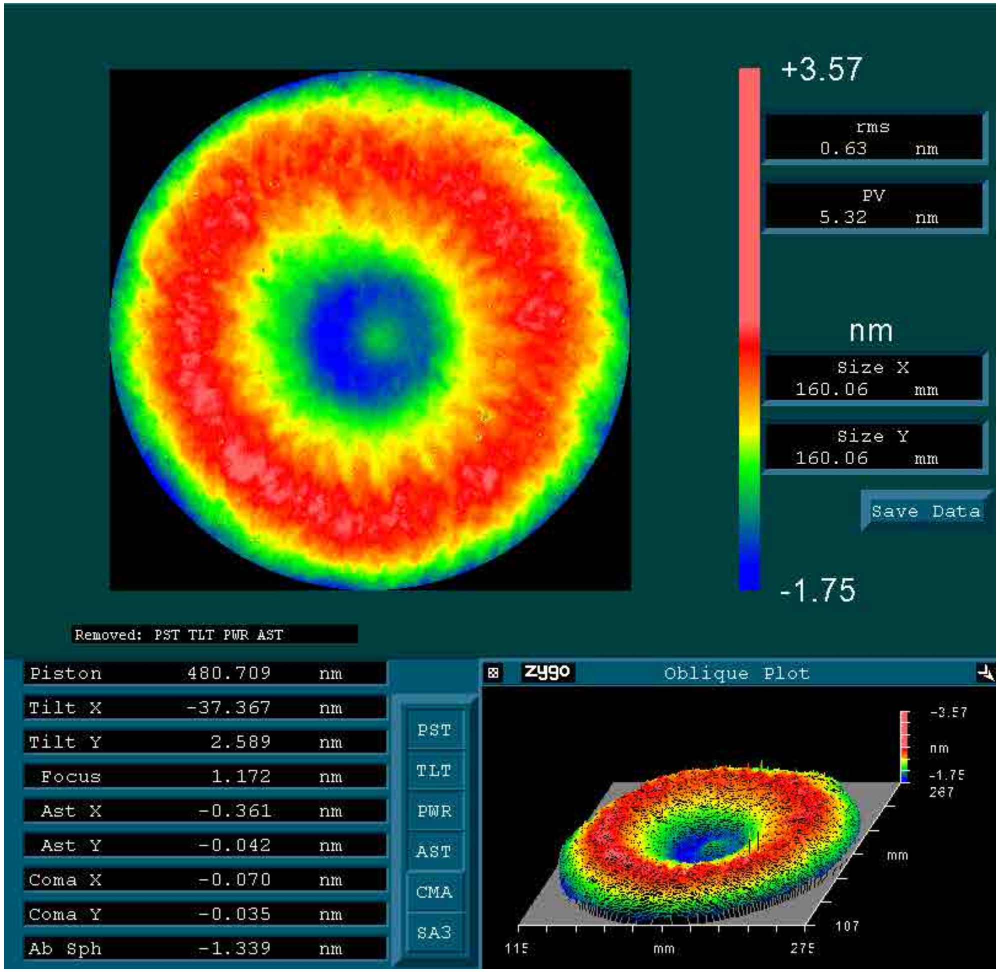
3.2 Uniformity improvements

- Blurring & interference technique: spiral pattern reduced by a factor 6



3.2 Uniformity improvements

- No uniformity change



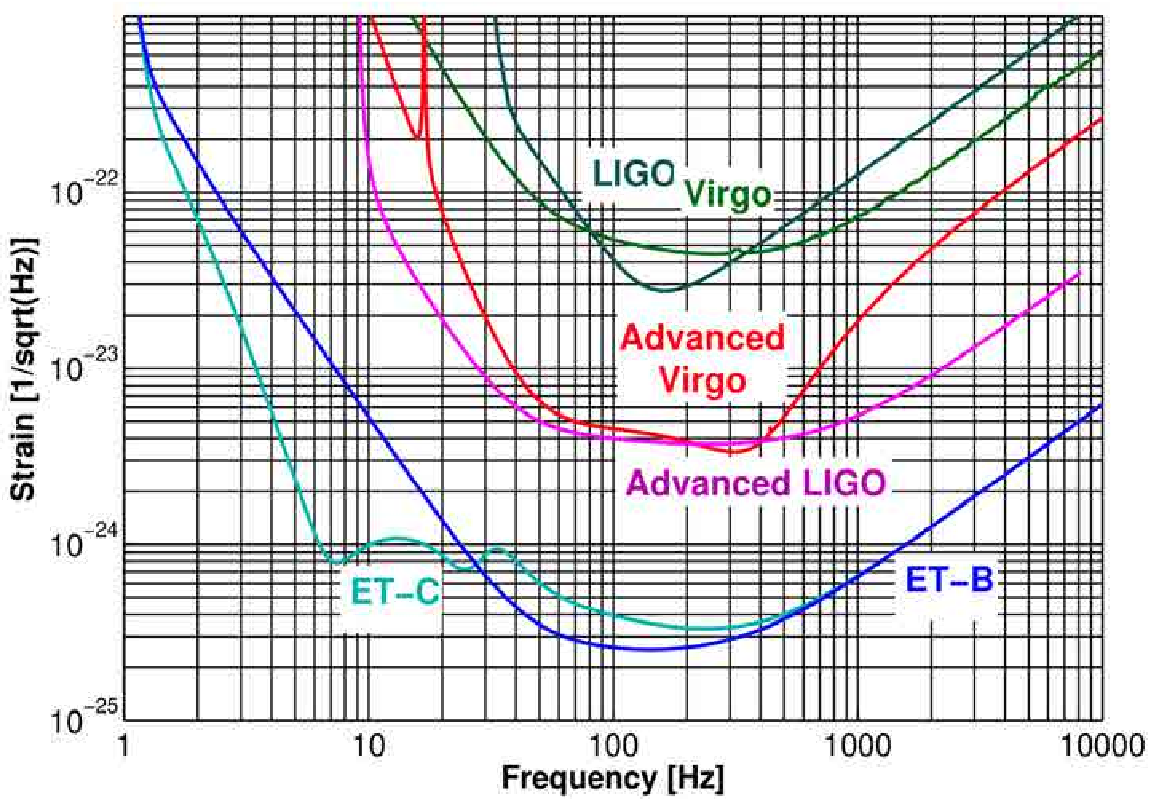
3.3 Results

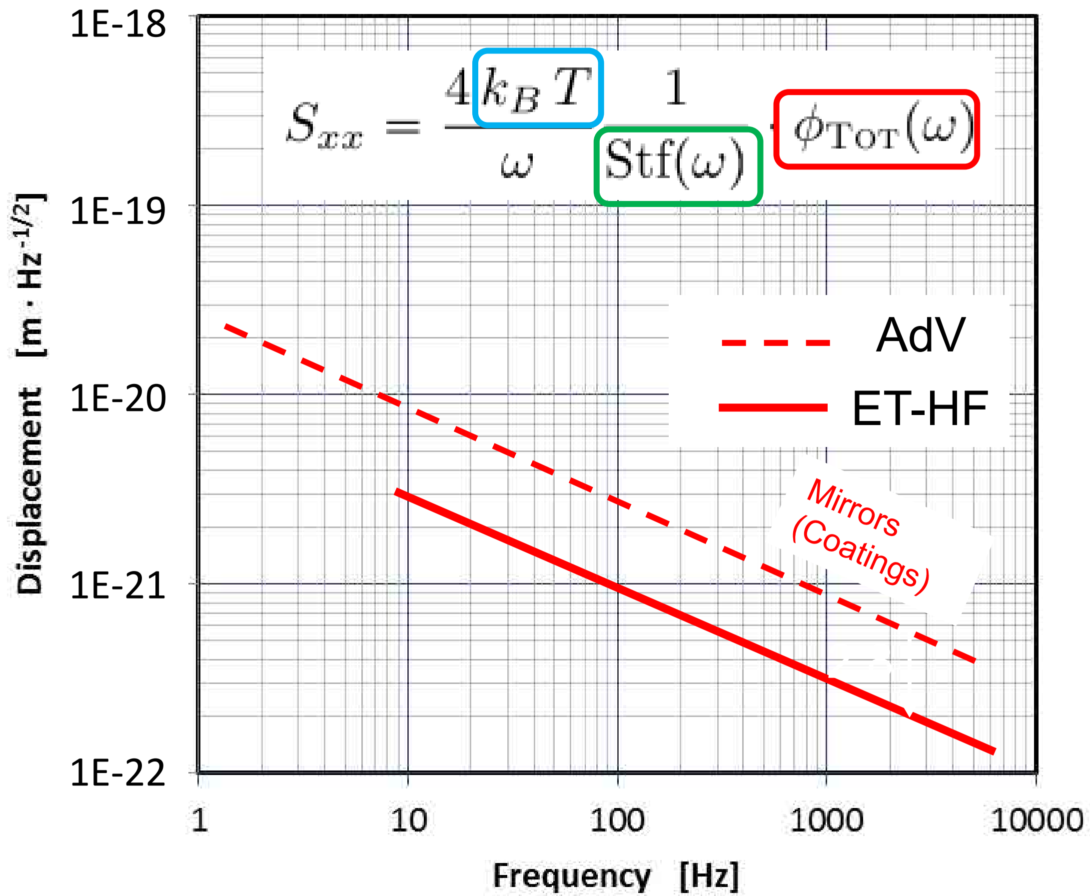
- 20 Test masses (10 ETM + 10 ITM) delivered to AdV. LIGO between 2012 & 2015. 8 Installed
- More than 150 optics delivered to AdV. VIRGO whose 10 large optics
- Average absorption: 0.3 ppm @ 1064 nm on Ø 180 mm
- Average scattering on Ø 180 mm :
  - ITM: 3.7 ppm
  - ETM : 4.9 ppm
- All AR < 100 ppm @ 1064 nm for AdV. VIRGO optics, best 13 ppm on Ø160 mm

The mirrors used in the LIGO interferometers for the first-detection of gravitational waves OIC 2016

3.3 Results

4.The future: towards the third generation





Coating ThNs reduction comes from:

Temperature: 20 K

Beam Size: Ø 600 mm

Loss angle : new material?

Conclusion

- More than 20 years of research and development.
- Strong interaction between process, metrology, simulation, technology…
- No revolution : improvement step by step
- Not a single know how but addition of several skills

LMA team past & present

LMA activities

- Optics for advanced gravitational waves detectors:
  - Adv. VIRGO, AdV. LIGO
- R&D for the third generation: ET
- Involved in ANR projects:
  - Minotore, Mighty Laser, GRANIT…
- Collaboration with french industrial groups:
  - SAGEM, Thalès
- Low losses coatings for international experiences: Japan, Russia, Italy, Australia, Germany

LMA activities

- New large IAD coating chamber for astronomical components: ESPRESSO, DESI….

Thank you!