Virgo_nEXT

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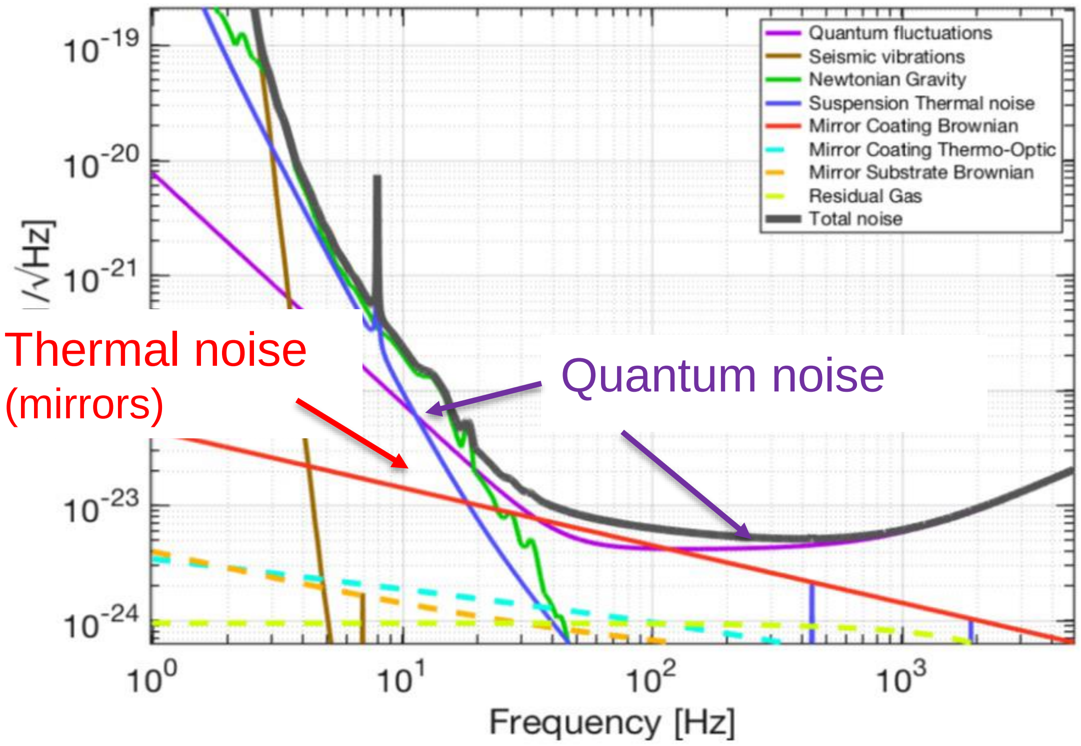
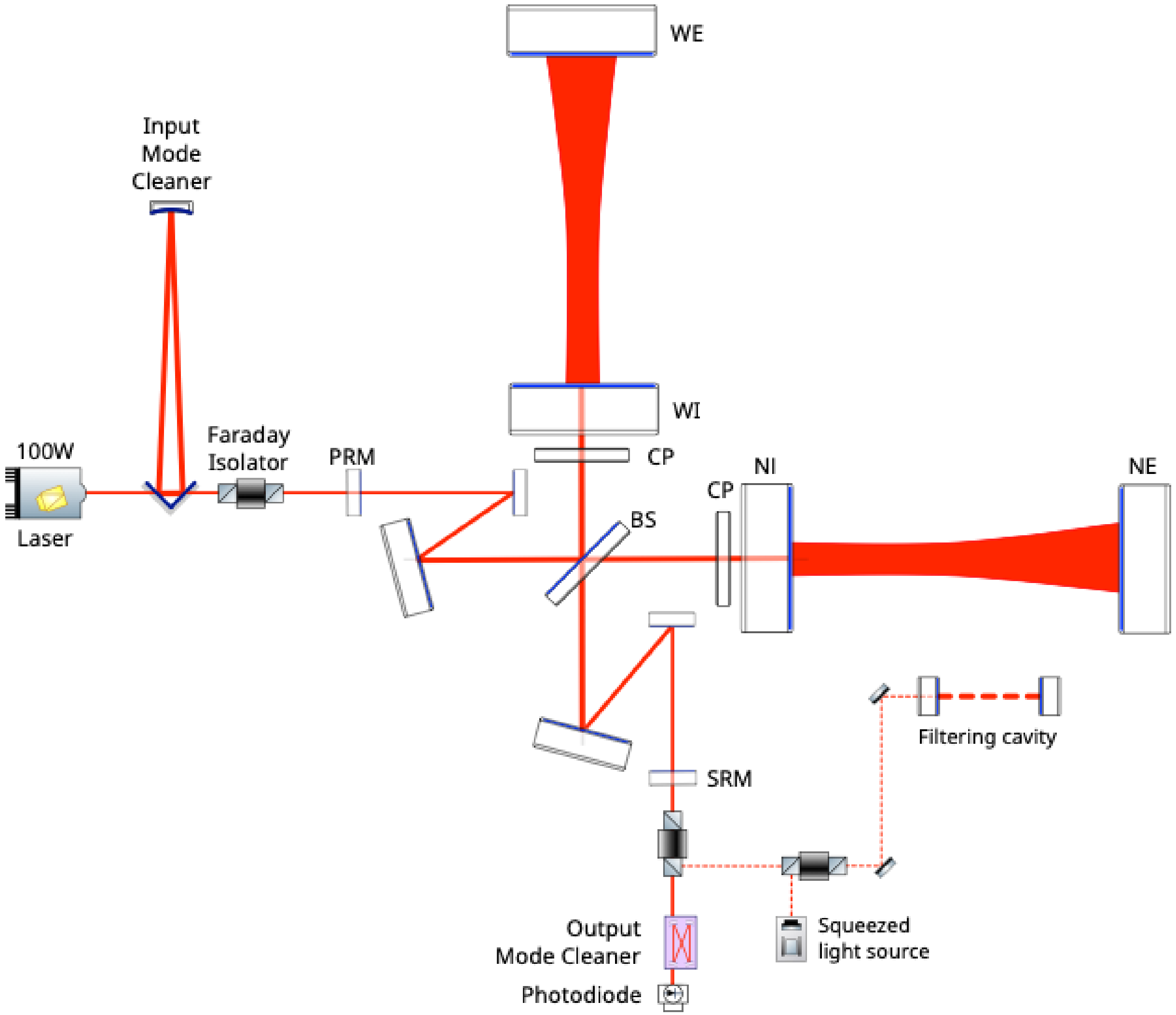
CS IN2P3, 3-4 July 2023

Outline

- Virgo_nEXT detector:
  - Optical configuration
  - Detector upgrades
- IN2P3 role
  - Detector developments and R&D
  - Data analysis
- Synergies with ET
- Conclusions

- From O5 to Virgo_nEXT:
  - Stable recycling cavities
  - Further reduction of quantum noise
    - Higher laser power
    - Improved squeezing
  - Further reduction of thermal noise
    - Improved coatings

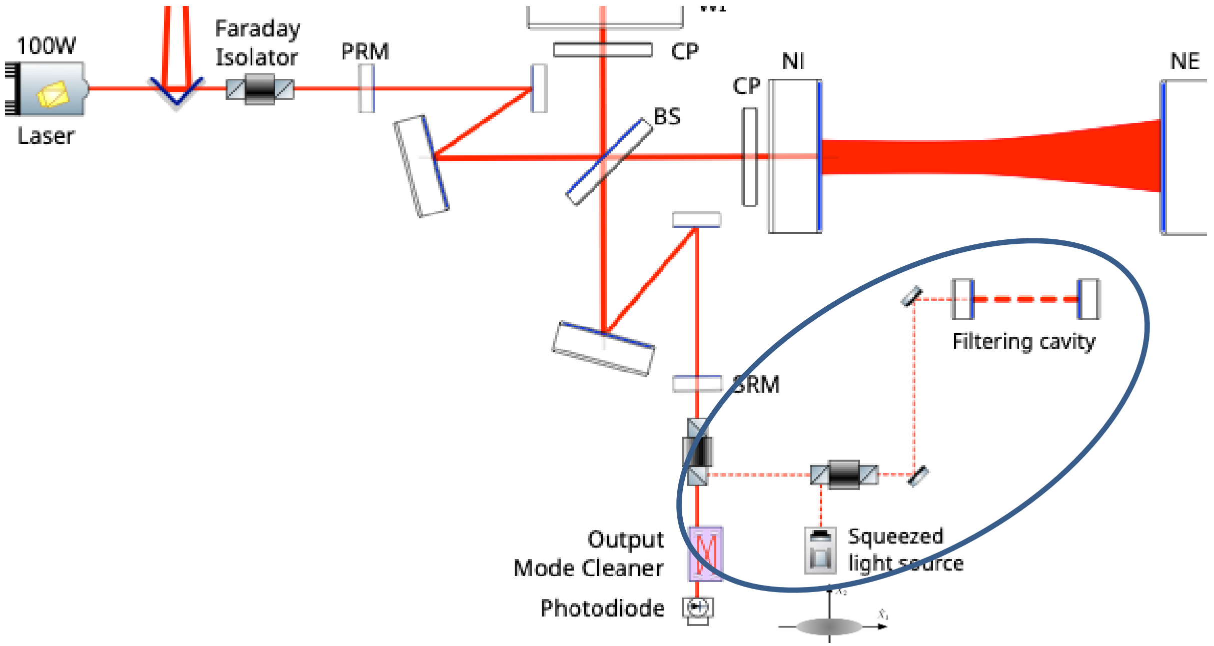




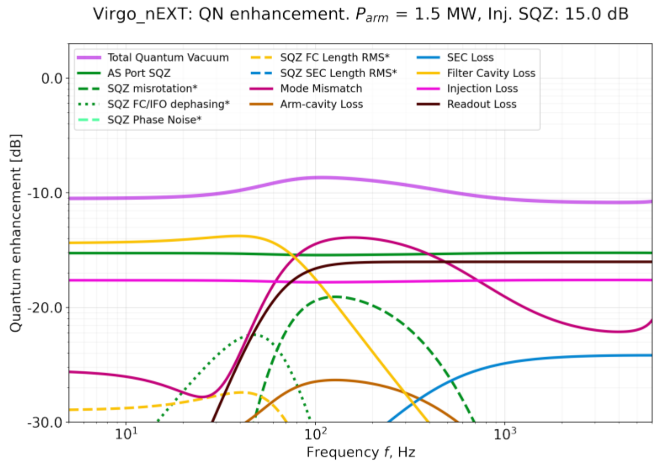
Virgo_nEXT parameters

Parameter	O4 high	O4 low	O5 high	O5 low	post-O5low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 dB	6 dB	10.5
Payload type	AdV	AdV	AdV	AdV	Triple pendulum
ITM mass	42 kg	42kg	42 kg	42 kg	105 kg
ETM mass	42 kg	42kg	105 kg	105 kg	105 kg
ITM beam radius	49 mm	49 mm	49 mm	49 mm	49 mm
ETM beam radius	58 mm	58 mm	91 mm	91 mm	91 mm
Coating losses ETM	2.37e-4	2.37e-4	2.37e-4	0.79e-4	6.2e-6
Coating losses ITM	1.63e-4	1.63e-4	1.63e-4	0.54e-4	6.2e-6
Newtonian noise reduction	None	1/3	1/3	1/5	1/5
Technical noise	"Late high"	"Late low"	"Late low"	None	None
BNS range	90 Mpc	115 Mpc	145 Mpc	260 Mpc	500 Mpc

- Aim: increase the squeezing level up to 10dB
  - ⇒ Reduce optical losses and scattered light
    - Improved optics
    - Reduce losses inside Faradays
    - Improve mode matching
    - Improved output mode cleaner
    - Squeezed light source under vacuum?
  - ⇒ Reduce phase noise
    - Improved controls



Parameter	O5	Initial post-O5	VnEXT
Injected squeezing	12 dB	12 dB	15 dB
injection losses	6.5%	5.5%	1.8%
FC losses	30 ppm	30 ppm	20 ppm
Readout losses	6%	4.5%	2.5 %
Arm-cavity roundtrip losses	75 ppm	75 ppm	75 ppm
Signal extraction cavity (SEC) roundtrip losses	1000 ppm	1000 ppm	500 ppm
Phase noise	25 mrad	15 mrad	10 mrad
Mismatching squeezing - filter cavity	0.5%	0.5%	0.25%
Mismatching squeezing - interferometer	2%	1%	0.5%
Measured squeezing at high-frequency	**5.5 dB**	**7.5 dB**	**10.5 dB**

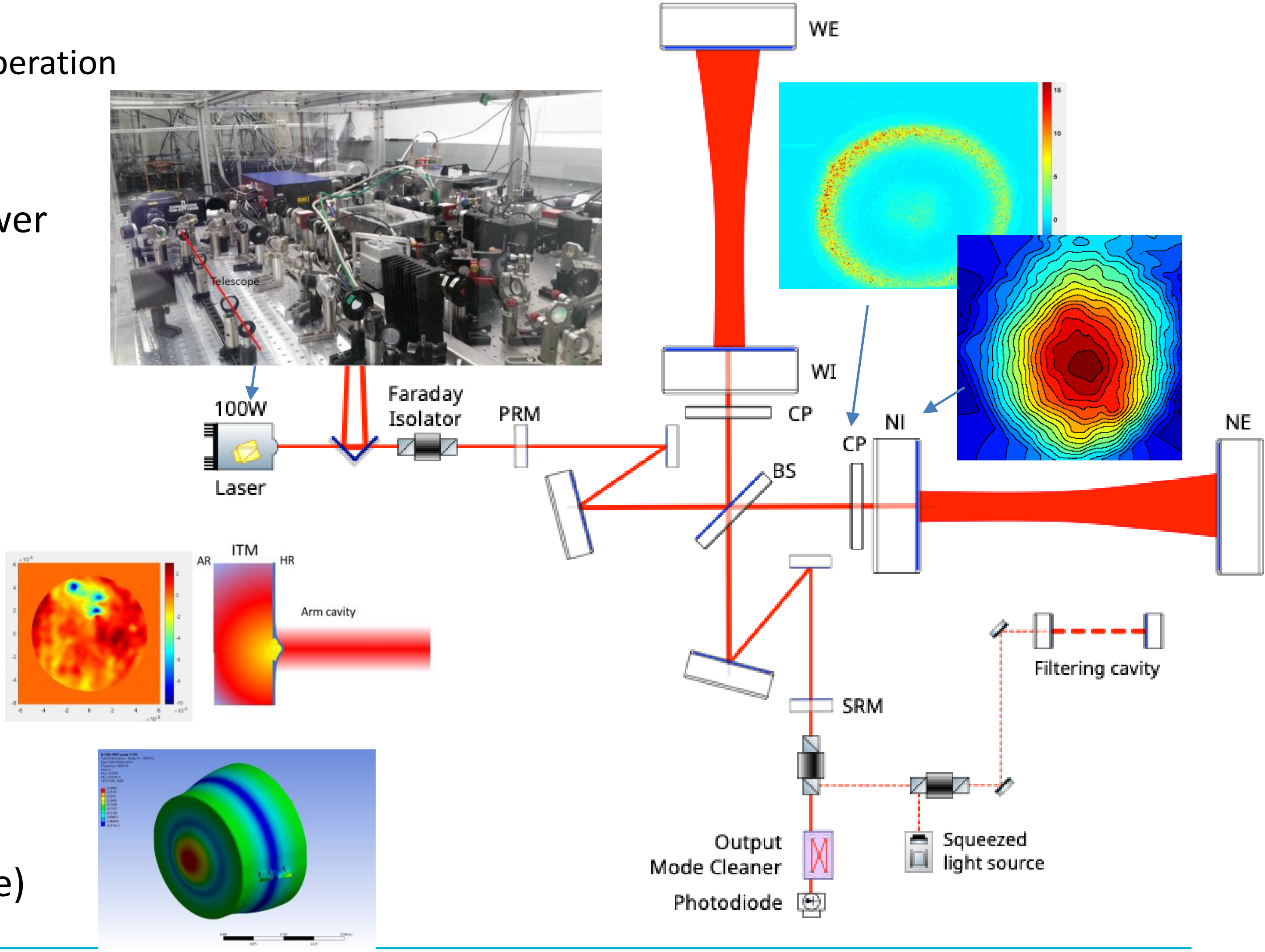


- Increase the laser power
  - Fiber laser at 500W
    - Technology exists, to be tested for long term operation and in terms of noise (frequency, power,...)
    - Improved stabilisation
  - Optical components compatible with high power operation:
    - Electro-optics modulators, Faraday isolator,...

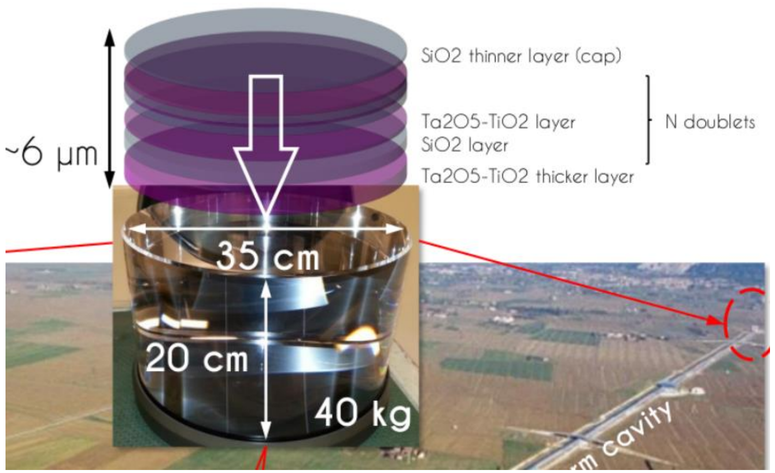
- Improved compensation of thermal effects
  - for main ITF mirrors

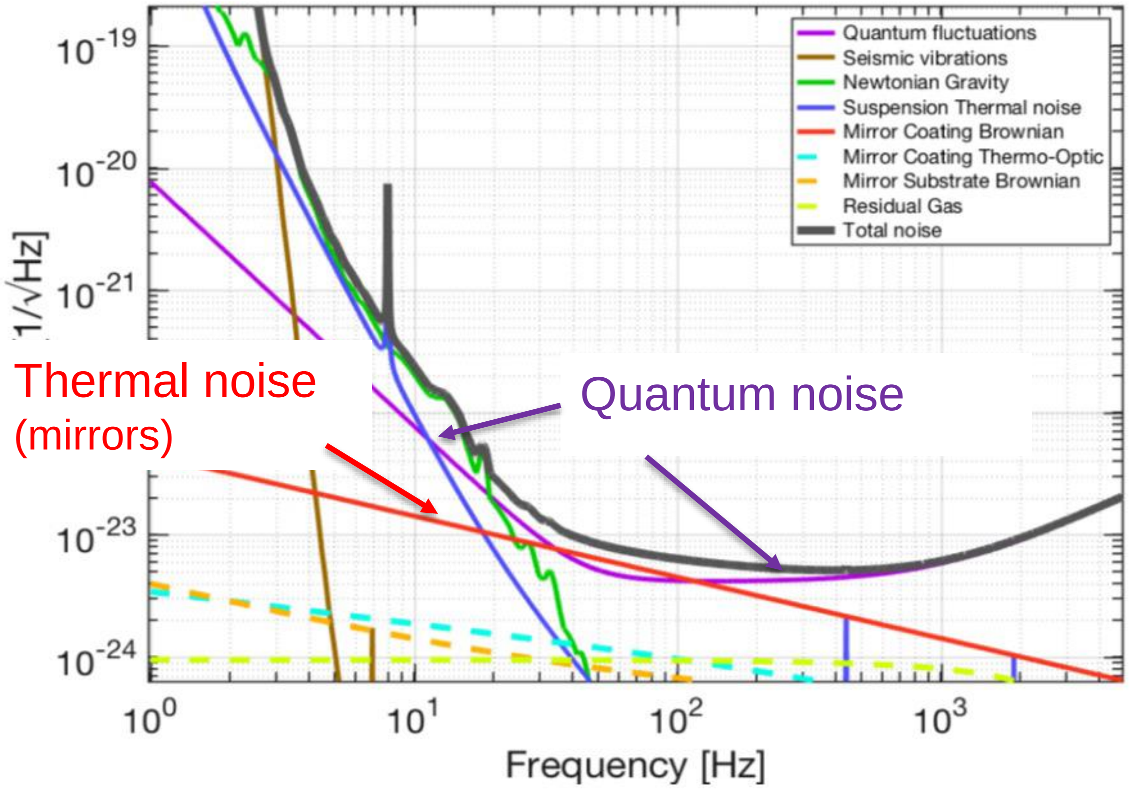
- Improved mirrors coatings
  - Reduce the presence of point absorbers

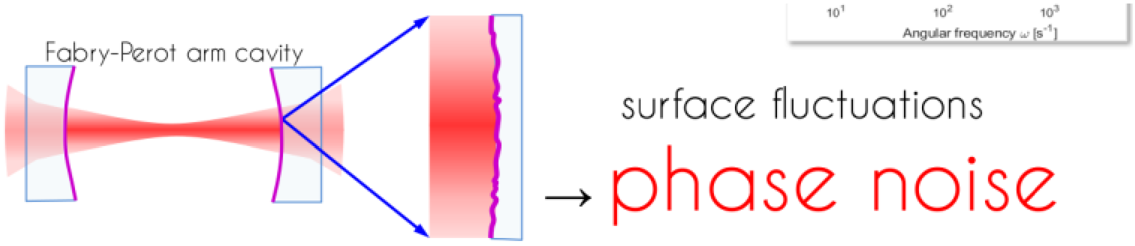
- Control of parametric instabilities
  - New system to be developed (passive or active)



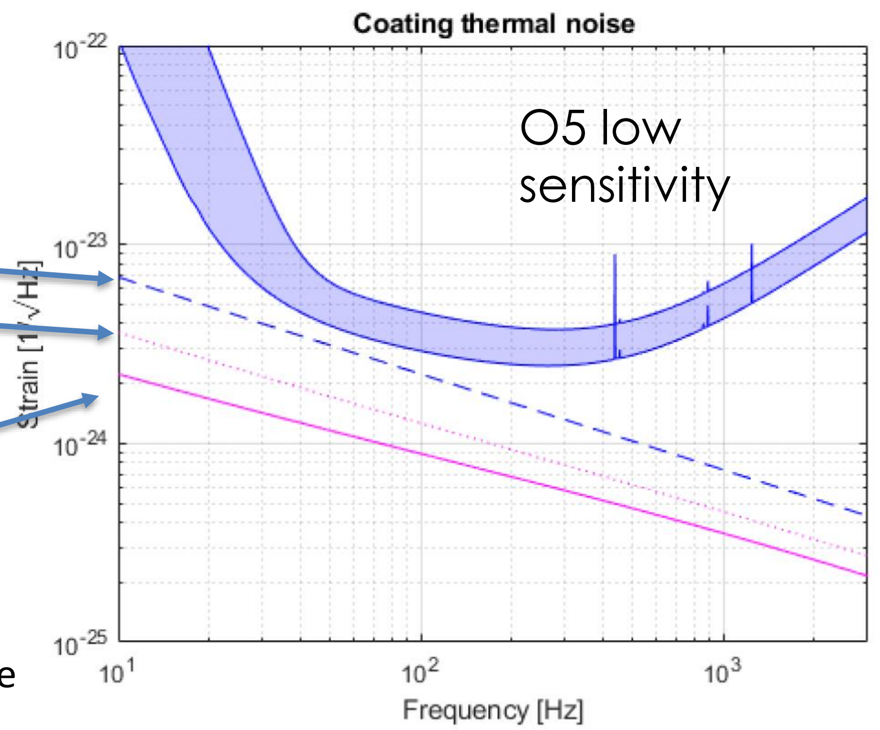
- Mirror’s thermal noise limited by coating thermal noise
  - ⇒ New materials with lower mechanical losses to be found
  - ⇒ Chosen materials need also to have low absorption (<1ppm)
  - ⇒ Quality of coatings is important (~~point defects~~)



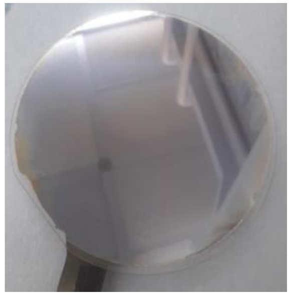


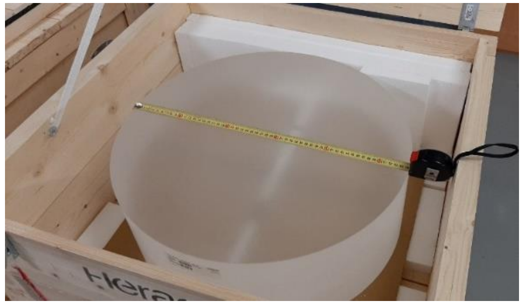


- Two types of materials:
  - Amorphous coatings
    - Used up to now
    - Improvements ongoing for O5 (mechanical loss /3)
    - Further improvements needed for V_nEXT
    - Deposition process and post treatment are crucial
    - Long optimisation process



  - Cristalline coatings
    - AlGaAs
      - Very good performance demonstrated on small surface (compatible with Virgo_nEXT's aim)
      - Technology to be upscaled: aim to reach 30cm
    - Crystalline oxides:
      - Promising on large areas
      - Need to be demonstrated and developed

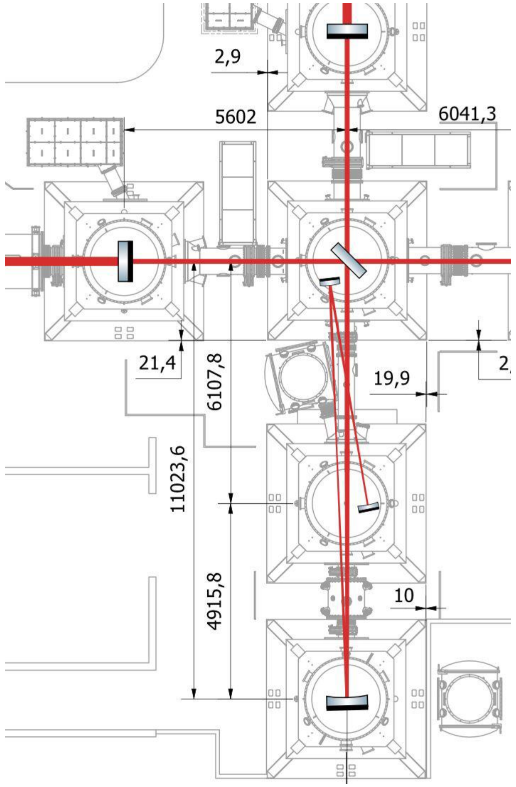




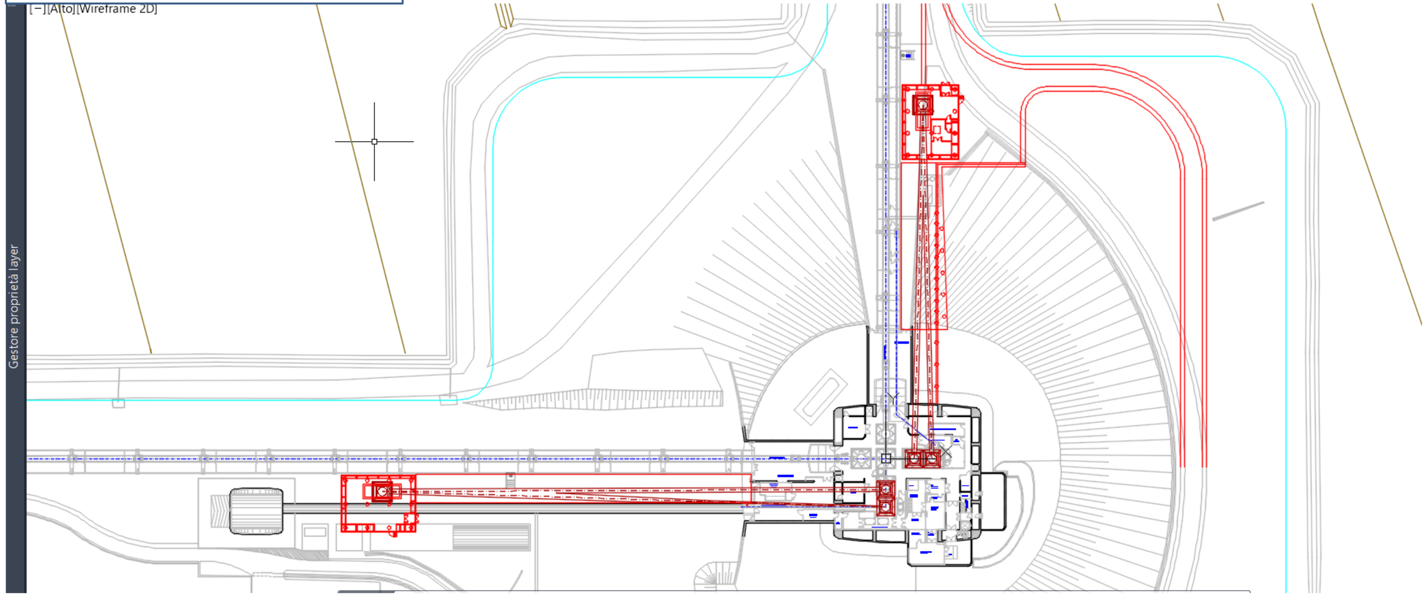
- Stable recycling cavities require to increase the length of these cavities
  - Several solutions to be studied (a long study was already pursued in 2010-11 for AdV)
  - Need well defined requirements => simulation studies
  - A lot of hardware to be developed/modified:

    vacuum, towers, suspensions, optics and optical benches

Internal solution

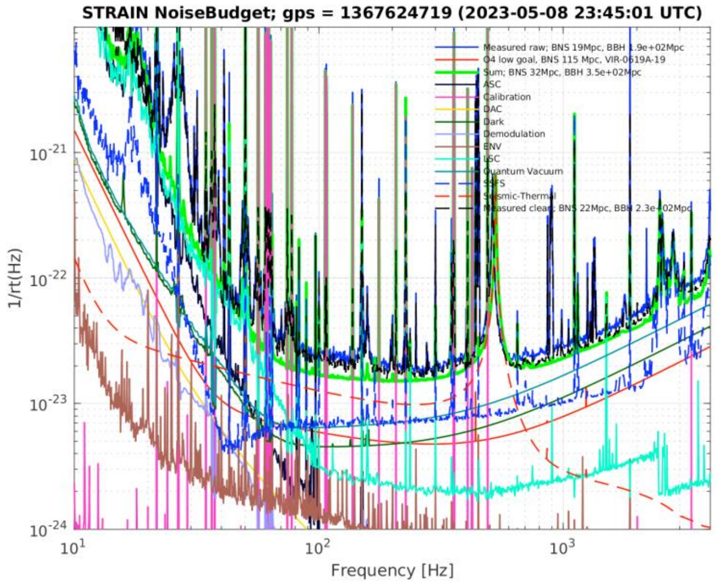


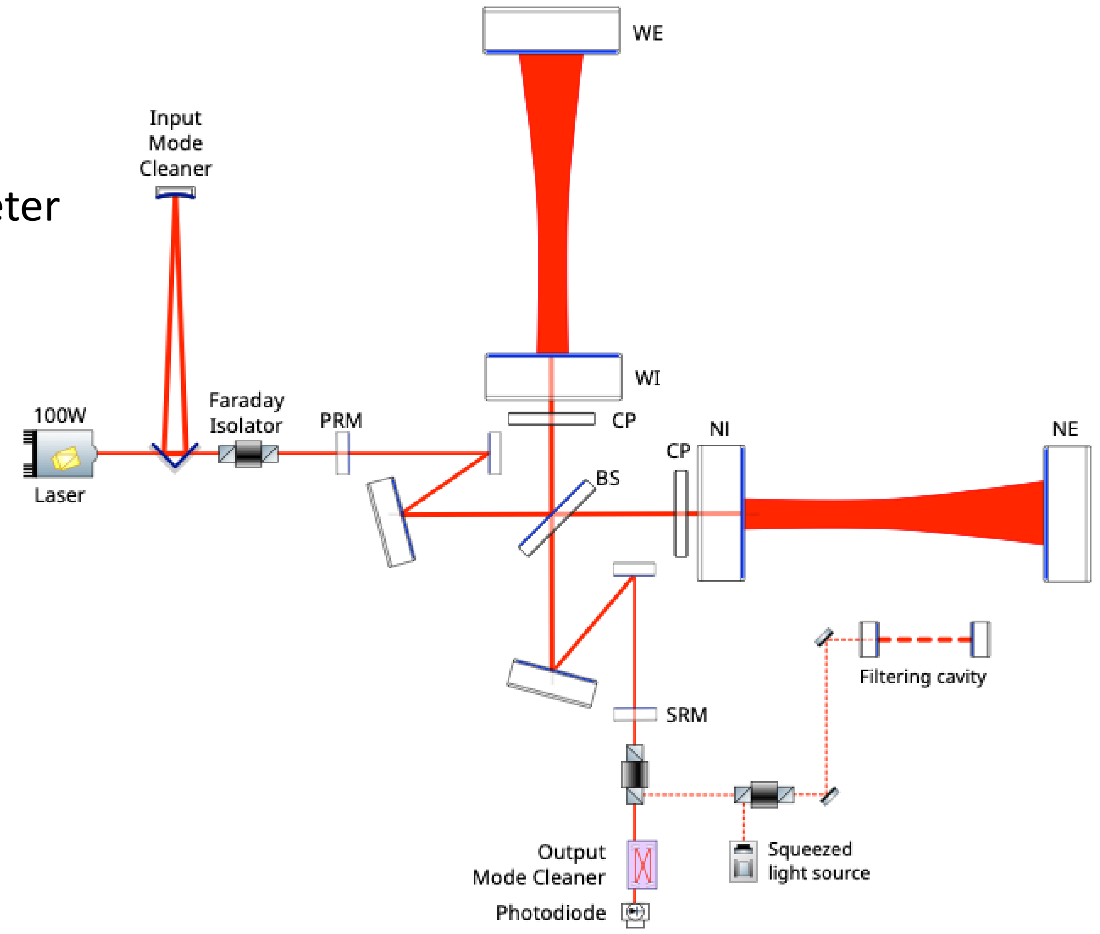
External solution

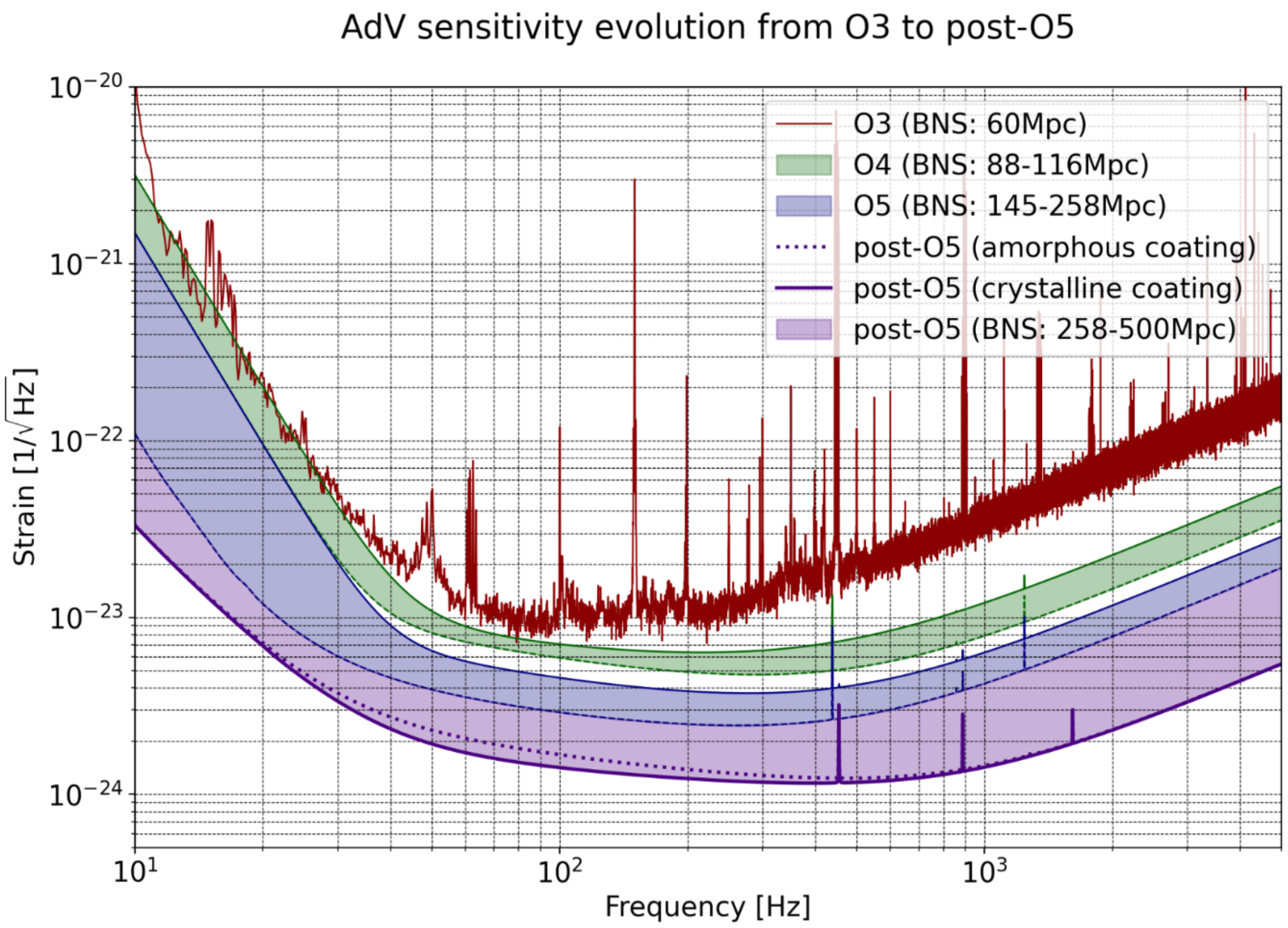


- Technical noises introduced through
  - the input beam stability (frequency, intensity, jitter,...)
  - the hardware and software used to control of the interferometer
    - Electronic noise of photosensors
    - Actuators's noise
    - Environmental electromagnetic noise
  - Light backscattered into the interferometer
    - By the optical elements, photodiodes,...

- Need to be reduced as the fundamental noises are lowered






AdV sensitivity evolution from O3 to post-O5
O3 (BNS: 60Mpc)
O4 (BNS: 88-116Mpc)
O5 (BNS: 145-258Mpc)
post-O5 (amorphous coating)
post-O5 (crystalline coating)
post-O5 (BNS: 258-500Mpc)
Strain [1/√Hz]
Frequency [Hz]
10⁻²⁰
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10¹
10²
10³

- March 2021: Virgo_nEXT study initiated
- Two committees formed:
  - Committee 1: Scientific potential
  - Committee 2: Detector design
- March 2022: Virgo_nEXT Concept study released (140 pages document)
- June 2022: Virgo_nEXT presented to EGO council and French Research Ministry
- January 2023: Virgo_nEXT coordinator appointed
- January 2023: 2 committees formed to address two main points:
  - Coating options
  - Need of stable recycling cavities
- July 2023: Finalizing preliminary plan for R&D
- December 2024: Expected Virgo_nEXT Technical Design report
- 2024-2029: Virgo_nEXT R&D and components development
- 2029: end of O5 LVK data taking
- 2032-2033: Possible Virgo_nEXT first data taking

- IN2P3 Laboratories: APC, IJCLab, IPHC, LAPP, LPC/Ganil, IP2I, L2IT, Subatech, ARTEMIS* - 81 FTE (139 persons)

- Other CNRS laboratories from INSIS (Institut Fresnel), INP (iLM, LKB) & INSU (LUTH-observatory)

- 11 CNRS groups represented at Virgo Steering Comitee (total: 35 groups)

- IN2P3 responsabilities:
  - Responsabilities in LVK search groups
  - Members of Virgo Executive committee
  - Management and technical responsabilities in Advanced Virgo+ and related R&Ds

Lab	FTE Ing/Tech	FTE Researchers	FTE total	persons
APC (Paris)	2	6.95	8.95	18
ARTEMIS (Nice)	1.35	6.65	8	28
IJCLab (Orsay)	1	8.7	9.7	14
IPHC (Strasbourg)	2	5.6	7.6	12
LAPP (Annecy)	7	13	20	27
LPC/Ganil (Caen)	1	3.1	4.1	8
IP2I (Lyon)	10.4	7.4	18.2	23
L2IT (Toulouse)	0.7	1.95	2.65	6
Subatech (Nantes)	0.7	0.9	1.6	3
Total	26.15	54.55	80.7	139

* IN2P3 as 2nd affiliation

Technological developments:

Historical strong involvement in development, construction, installation and commissioning

- Mirror coatings and metrology
- Vacuum chambers
- Optical benches and components
- Squeezing techniques
- Low noise analog and digital electronics
- Interferometer calibration and signal reconstruction
- Design studies for stable recycling cavities
- (Laser source and parametric instabilities)*

⇒ See next slides

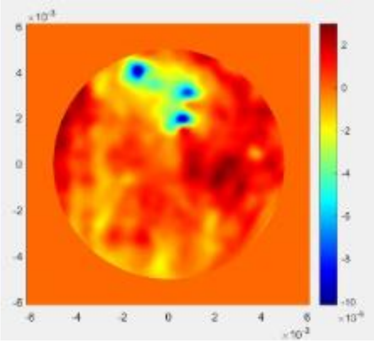
Plan for R&D for Virgo_nEXT in French labs being finalized

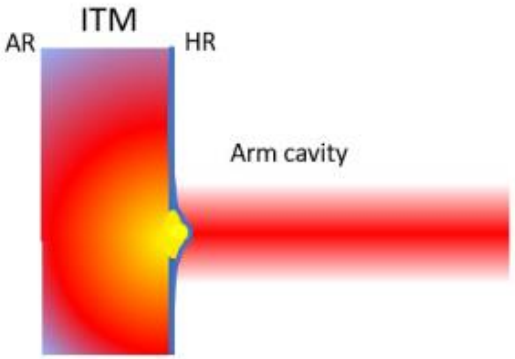
* IN2P3 as 2nd affiliation

LMA/IP2I

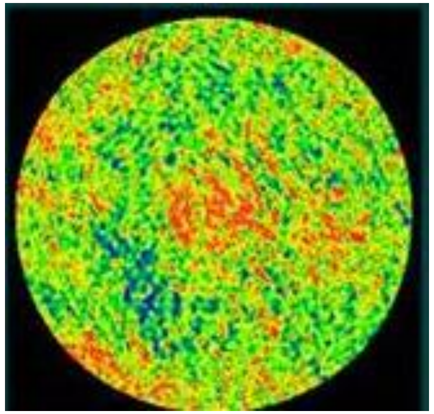
Very high quality coatings for high performance mirrors:

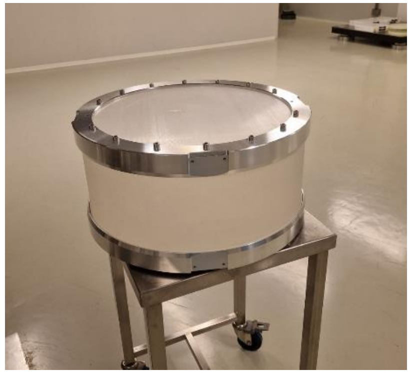
- Low defects:
  - Point absorbers (thermal effects):
    - Improved deposition process
    - New bench for characterisation will be developed
  - Point scatterers (optical losses):
    - Characterisation (PhD thesis, ANR submitted)
    - Tuning of deposition parameters



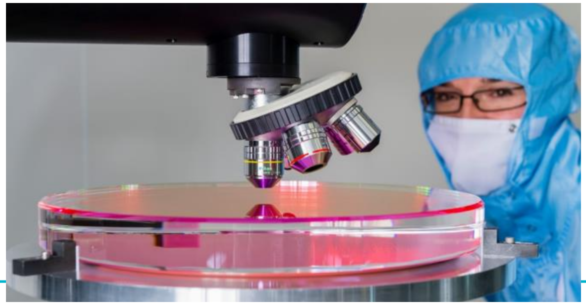


- Low anti-reflective coating (optical losses):
  - Improvement of the control of coating layer thickness





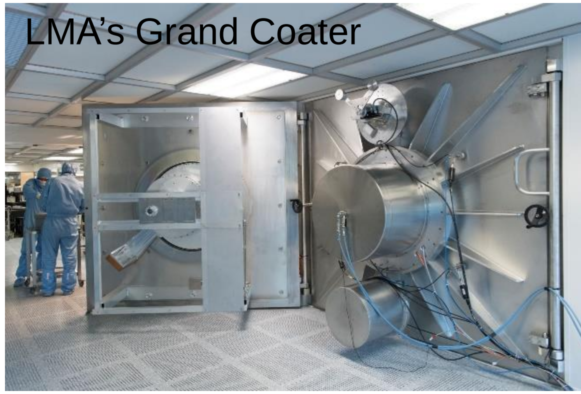
- Metrology



LMA/IP2I, LAPP

Reduction of thermal noise by a factor 3 wrt O5: new materials for coatings

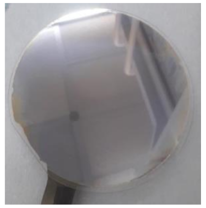
- Amorphous coatings:
  - LMA is the leading laboratory for amorphous coating on large optics for GW detectors
  - Dedicated chamber for R&D on materials (CMO IN2P3 Master project)
  - Deposition process in Grand Coater to be adapted to chosen material

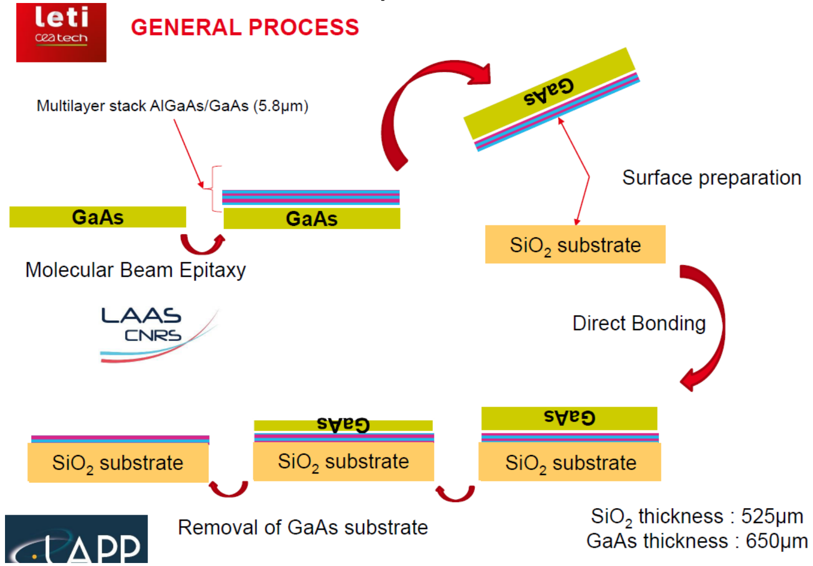


- Crystalline coating: AlGaAs
  - Production and characterisation of crystalline coatings (collaboration with CEA-LETI and LASS)

    => Demonstration of process on small sample
  - Process to be developed on larger samples:
    - Collaboration with industry essential (ANR submitted)
  - Themal noise measurement: optical setup to be developped

∅10cm

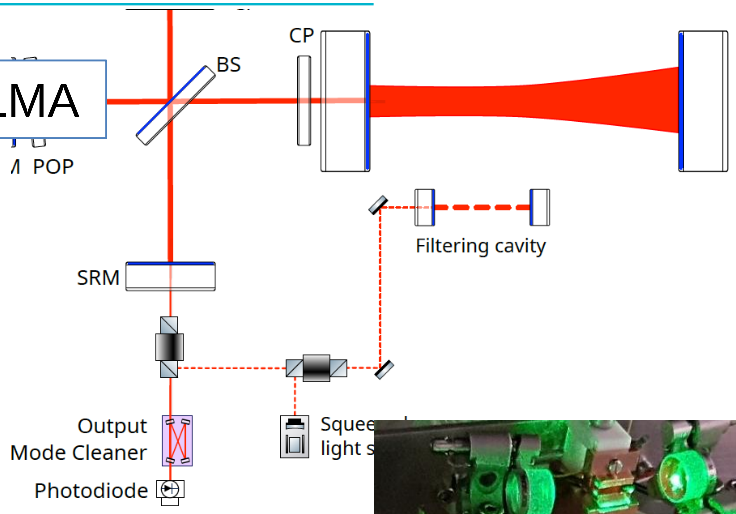


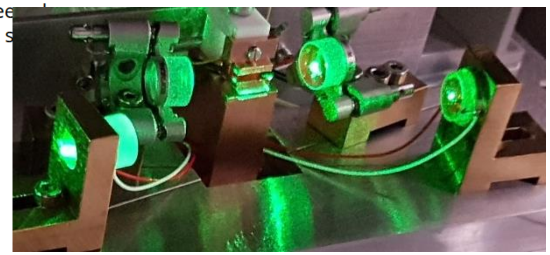


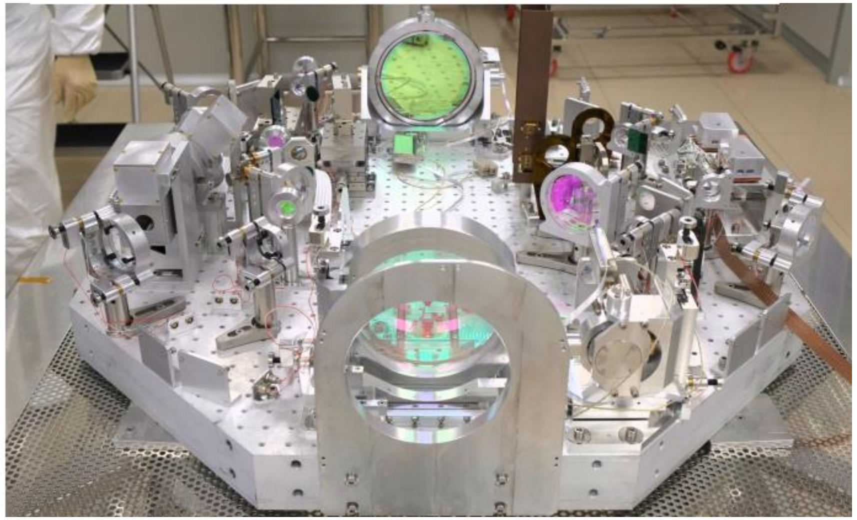
Improve the squeezing performance

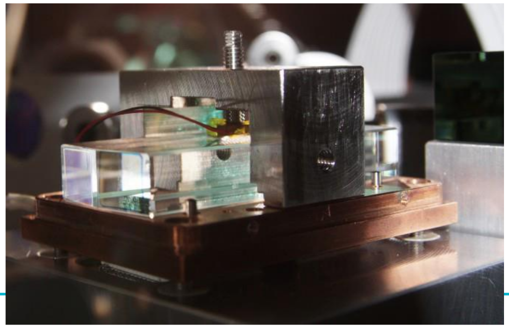
APC, IJCLab, L2IT, LAPP, IP2I/LMA

- Improved optics (see slide 14)
- Squeezing source under vacuum or new geometry?
  - To be decided based on limitation observed in O4 (scattered light)
- Improved mode matching
  - Sensing technique to be developed
  - New mode matching telescope with adaptive optics
- Improved output mode cleaner
  - New type of cavity to be developed with lower absorption & scattering
- Low noise photodiodes









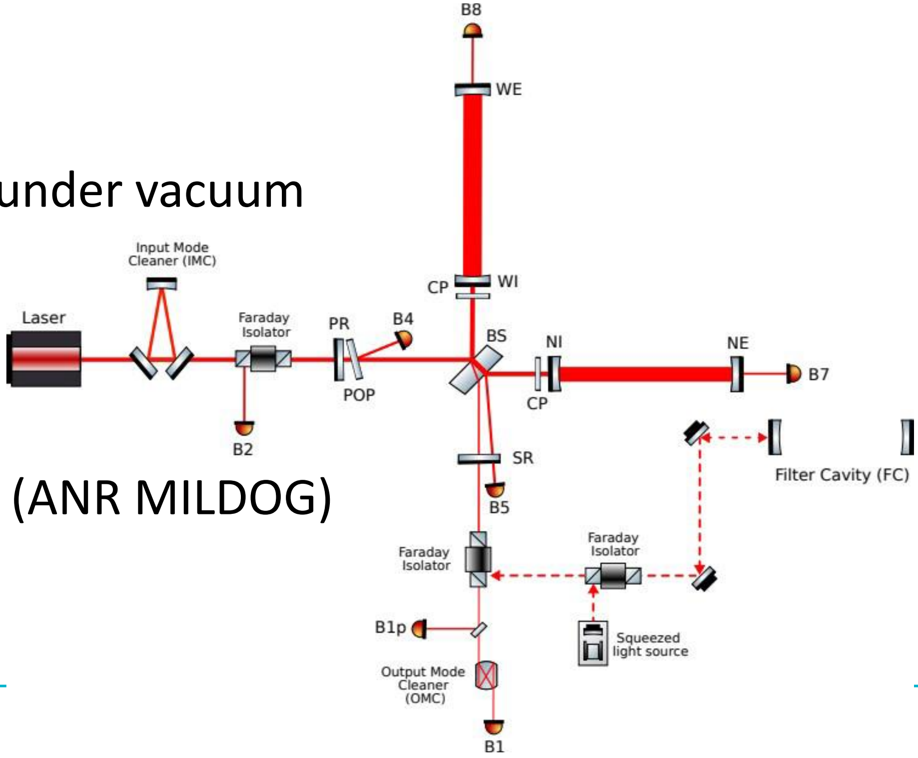
LAPP , APC, L2IT

IN2P3 responsabilities/expertise:

- Vacuum towers
- Mechanics of optical benches
- Optical components: mirrors, beam dumps, diaphragms, ...
- Output mode cleaner cavity
- Mode matching telescopes

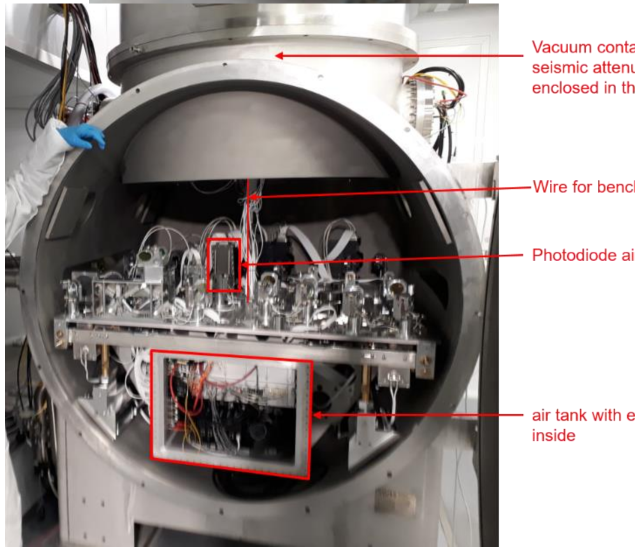
Stable recycling cavities will require:

- New/upgraded suspended benches under vacuum
- New mode matching telescopes



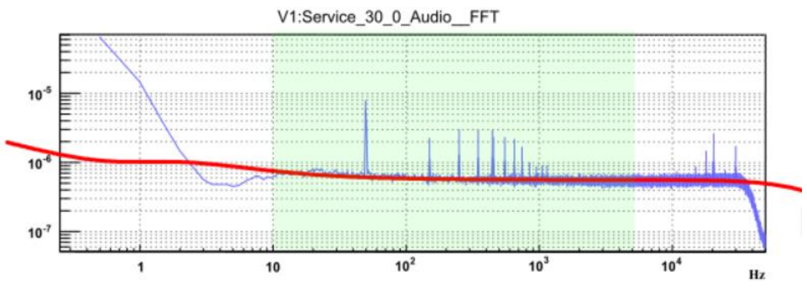
Reduction of scattered light:

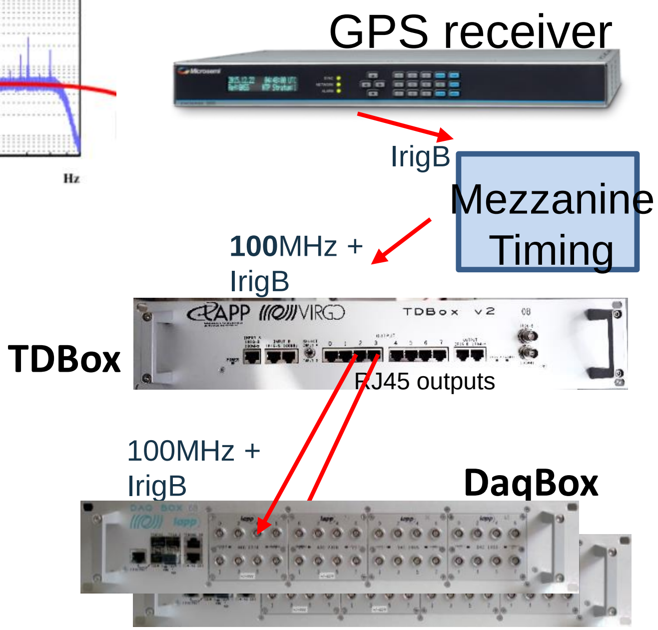
- Characterisation of optical elements (ANR MILDOG)
- Improved optical elements



LAPP , IPHC

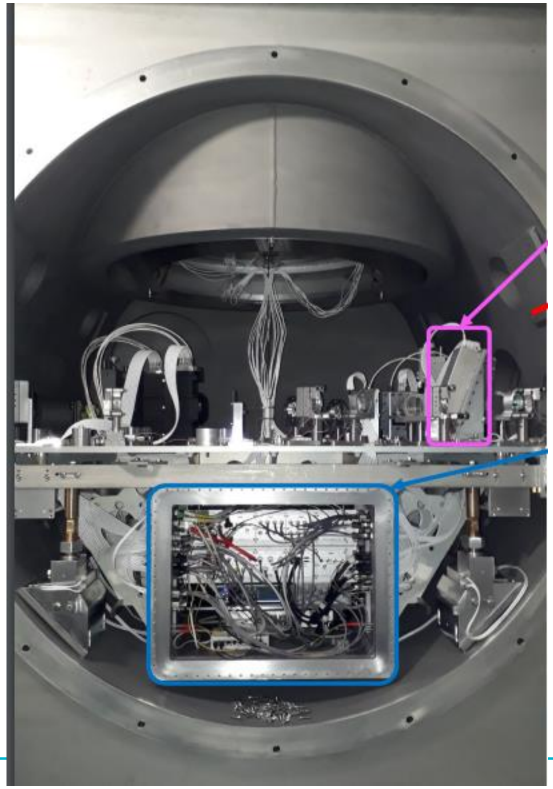
- IN2P3 responsabilities/expertise:
  - Analog electronics (photodiodes,...)
  - Digital electronics
  - Real time data treatment and acquisition
  - Slow control





- Reduction of technical noises:
  - Improved photodiode preamplifiers
  - Move digital electronics outside vacuum tank (R&D started with ENIGMAS Labex &USMB)

- Virgo_nEXT new instrumentation:
  - Additionnal/upgraded ADCs/DACs, RTPCs...

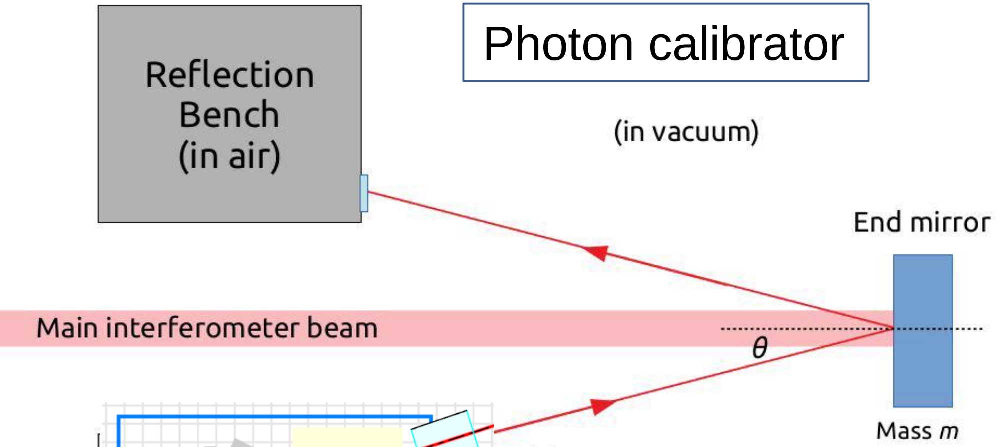


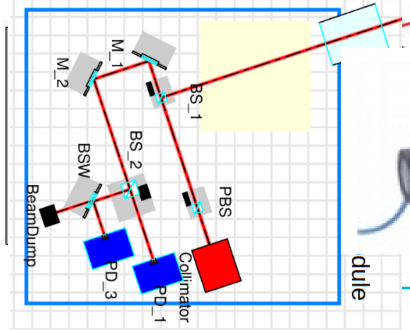
LAPP , IPHC

- IN2P3 responsabilities: all the calibration systems and the signal reconstruction
- Virgo_nEXT improved sensitivity => more accurate calibration systems:

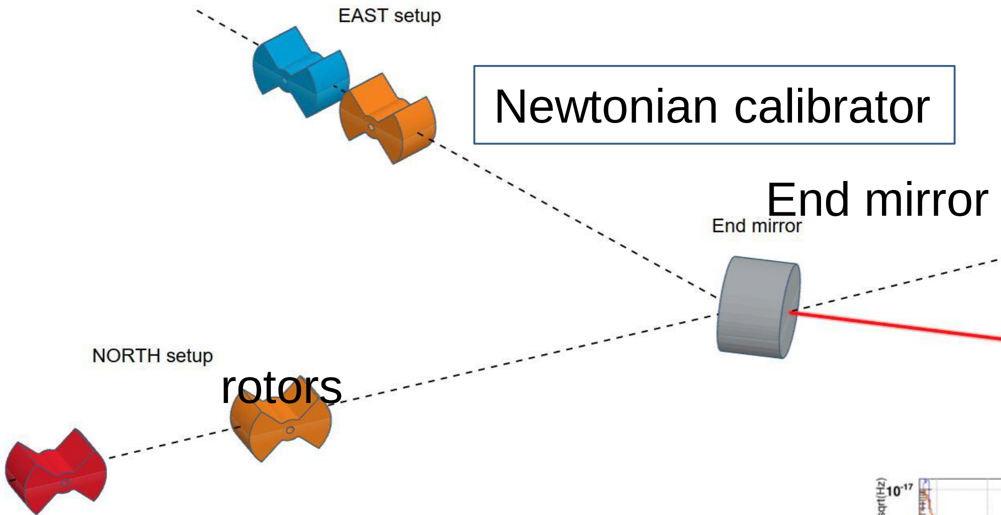
  - Photon calibrator: precise powermeters (under vacuum?) , electronics, upgrade of optical benches
  - Newtonian calibrator: improved seismic isolation, upgraded rotors
  - Signal reconstruction software: reduction of systematic uncertainties

Photon calibrator

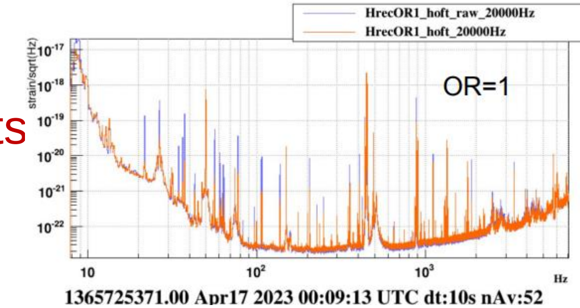




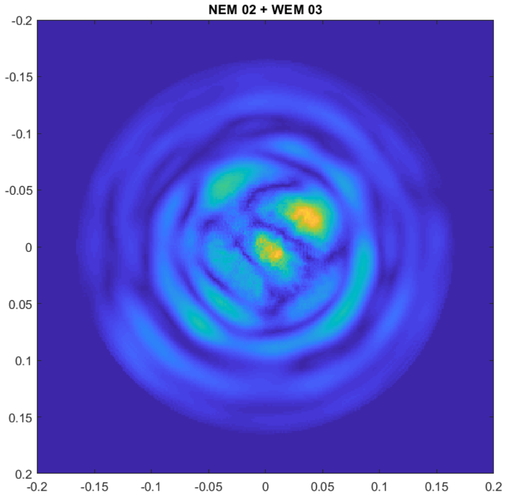
Newtonian calibrator



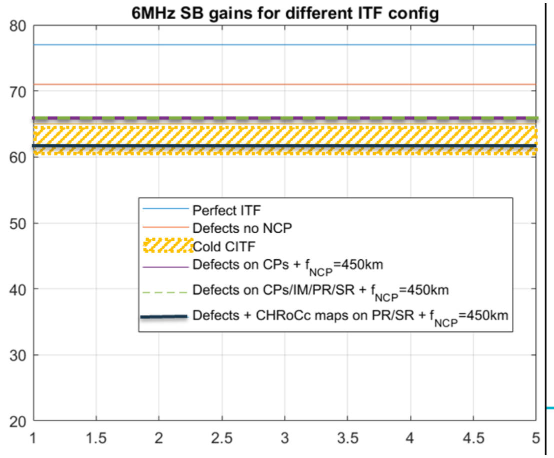
- Virgo_nEXT higher detection rate, multi-messenger alerts
  - Faster signal reconstruction (latency/10?)
  - Automation of some tools / monitoring

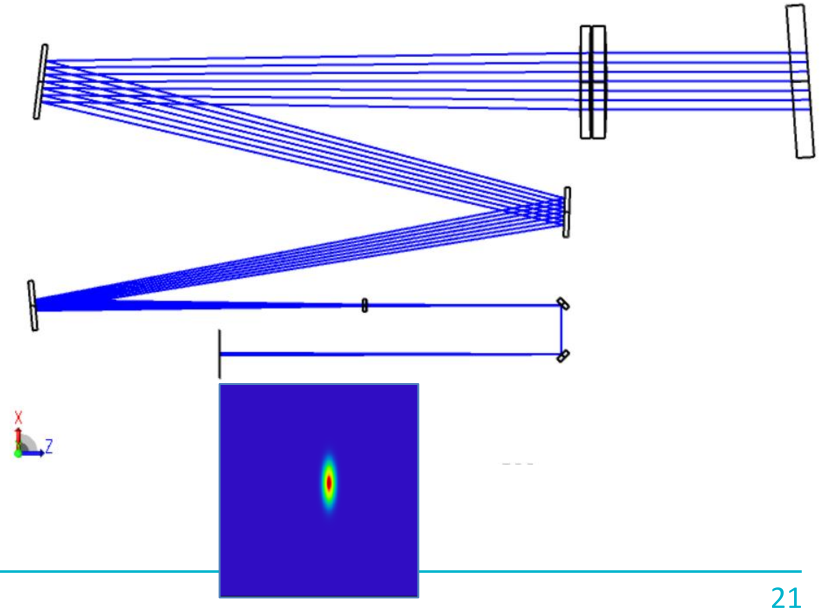


- IN2P3 implications
  - Development of optical simulation software (OSCAR,...)
  - Design studies using optical simulation tools (Zemax, Optocad, OSCAR,...)
  - Simulation studies for the understanding/anticipation of the interferometer behaviour:
    - Impact of defects and optical losses
    - Impact of high power
    - Coupling of technical noises



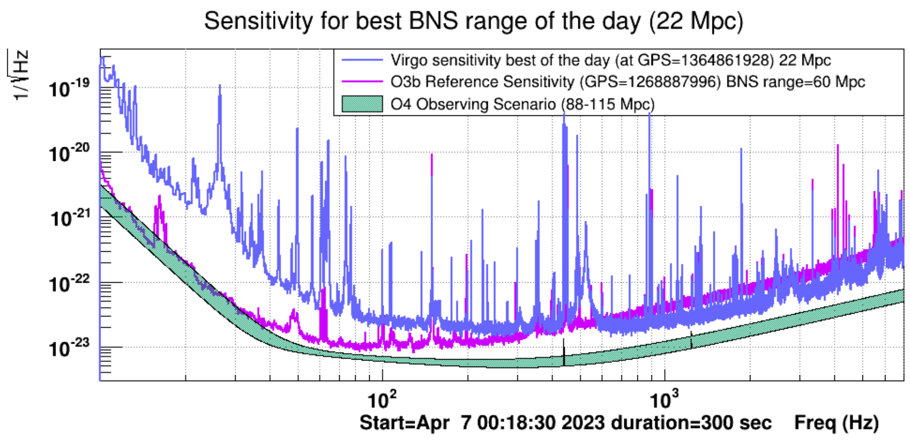
- Simulation studies are (more and more) essential for:
  - the understanding of Advanced Virgo+
  - the design of Virgo_nEXT (guided by AdV+ experience)





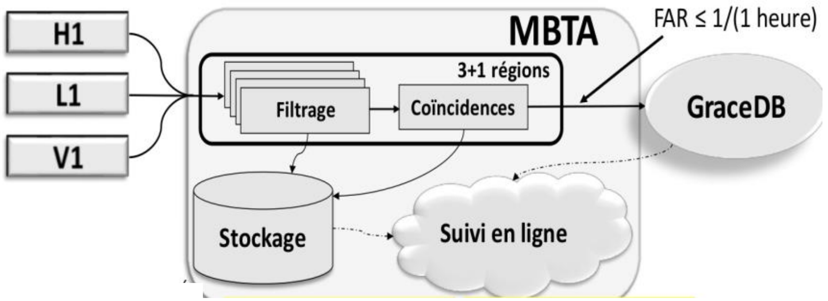
Data analysis and interpretation:

- Historic strong involvement in data analysis (from reconstruction to interpretation)
- Number of FTE increasing with time
- Number of covered topics increasing
  - Detector characterisation
  - Gravitationnal wave signal reconstruction
  - Search for transient GW signals
  - Search for stochastic GW background
  - Constraint on extremely dense matter
  - Cosmology
  - Multi-messenger astronomy
  - Open science

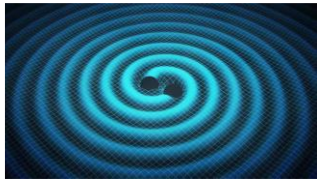


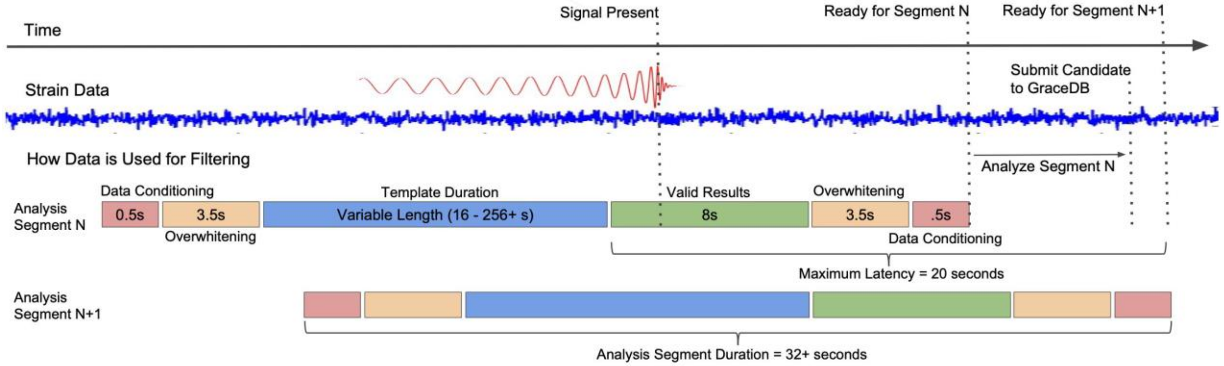
IJCLab, LAPP, IP2I, IPHC, IAP

- Search for poorly modelled source (“*bursts*” – *Supernovae,..*):
  - Development of pipelines
  - Coordination (Burst LVK working group)



- Search for coalescing binaries (BH, NS)
  - Main developpers of MBTA pipeline (online search)
  - Development and running of PyCBC pipeline
  - Waveform models, parameters estimation
  - test of modified gravity
  - Characterisation of GW polarisation content
  - Use of ML technique as alternative
  - Coordination (CBC LVK working group)





- Search for stochastic GW background
  - Search for astrophysical background
  - WG leadership
  - Development of searches in view of ET

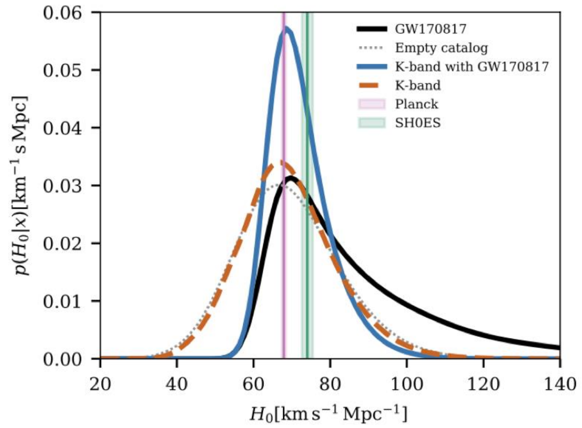
Constraints on extremely dense matter and cosmology

LUTH/LPC/Ganil

- Constraints on extremely dense matter
  - Recent expertise
  - Nuclear physics, dense matter inside neutron stars (coalescence signals)
  - Visibility in the LVK WG
  - Encouraging interfaces with the astronuclear and theory community

IP2I, APC, L2IT

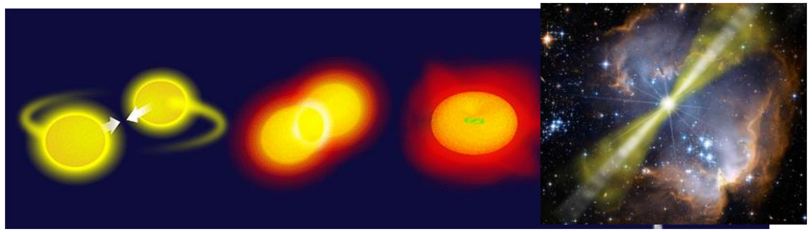
- Cosmology
  - Observation of GW170817 (O2) and many compact binary coalescence events (O3)
  - Increased person-power in the French groups
  - Analysis techniques, pipelines (Icarogw)
  - Theory and phenomenology
  - Tests of general relativity
  - Preparation for ET + contacts with LISA community
  - Coordination of LVK group “cosmology with CBC”

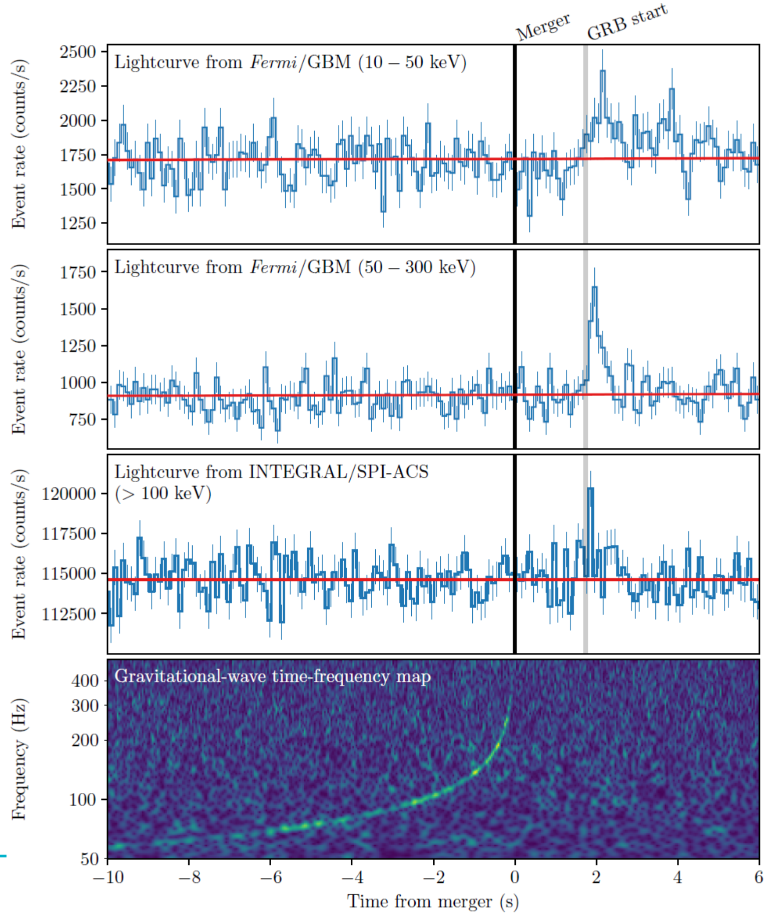


Multi-messenger astronomy and open science

IJCLab, LAPP, IPHC, APC

- Multi-messenger astronomy
  - Joint observation of GW signals and GRBs, EM follow up
  - Associated detections of GW and high energy neutrinos (with KM3NeT)
  - Electromagnetic follow up of GW alerts

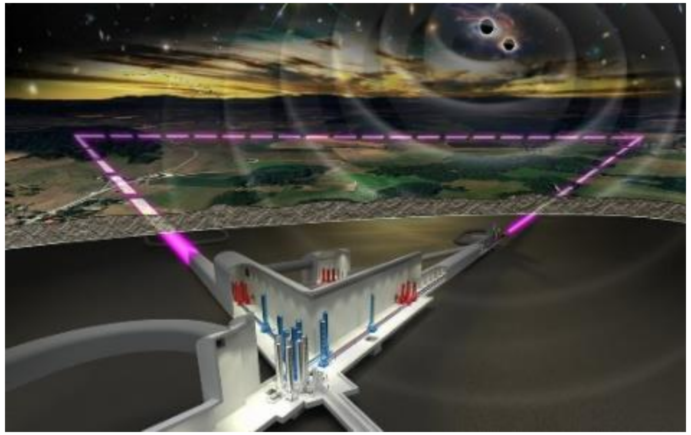


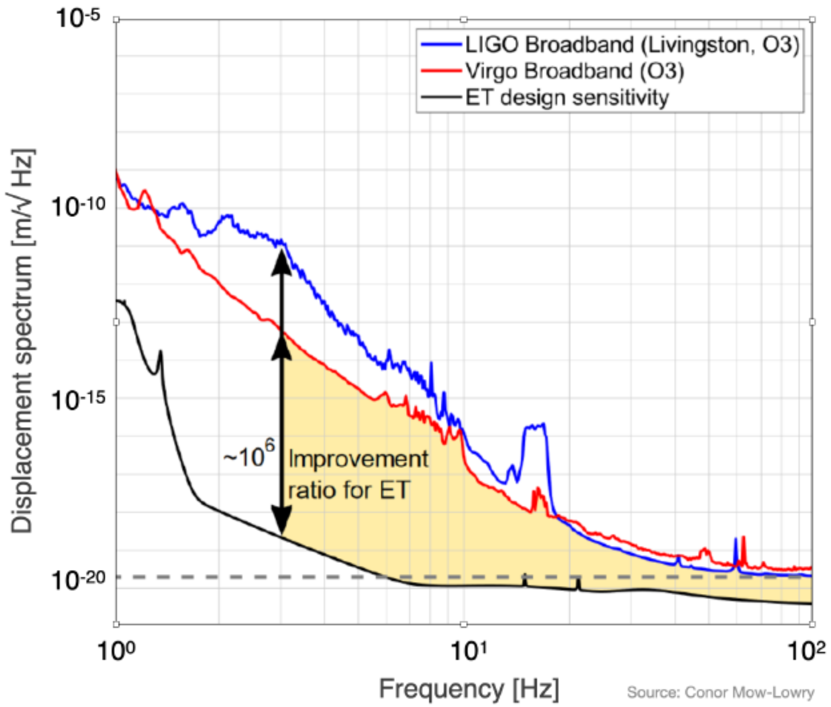


APC, IJCLab

- Open science
  - Gravitationnal-Wave Open Science Center (GWOSC)
  - Leading role in the release of data: technical and scientific aspects
  - Development of the public pipeline PyCBC

- Testing technologies for ET HF
  - Similar laser and arm power, similar radiation pressure
  - Similar squeezing level
  - Aiming for similar coating thermal noise
- Testing complex physical effects not testable on small prototypes
  - Thermal effects
  - Parametric instabilities
  - Precise calibration and fast reconstruction & handling of large events rate
- Testing methods for technical noises reduction at low frequency
  - Optimization of control methods
  - Noises subtraction
  - ⇒ Acceleration of ET commissioning
- Training detector experts
- Development of realistic detector simulation





Virgo_nEXT is an essential step:

- Push the potential of Virgo’s infrastructure to its limits
- Increase the science reach after O5 and before the start of ET
- Pave the way for ET: test the technologies on a real scale instrument / handle high rate events
- Keep the expertise of the experimental and data analysis community

IN2P3 teams are at the forefront:

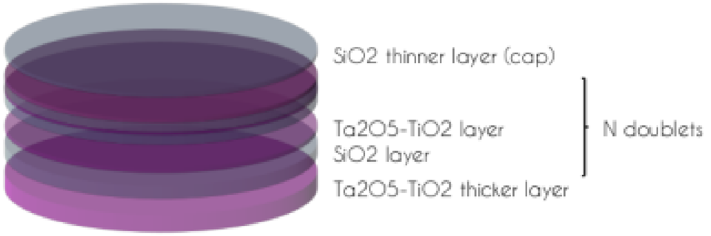
- Expertise on all the Virgo_nEXT items: technology and data analysis
- Implication in the Virgo_nEXT design
- R&D plan being built inc. synergies with ET

END

- High power (few 100 W) stabilized laser (intensity, jitter, frequency)
- High power optical components (EOM, Faraday)
- Low loss optical components (Faraday, mode cleaner cavities)
- Mitigation strategies for PI
- Improved thermal compensation systems
- Improved mirror coatings (low thermal noise, low absorption, low defects, low reflexion)
- Improved squeezed light source
- Development of mode matching sensors and actuators
- Improved control strategies
- Improved scattered light mitigation
- Improved payloads with reduced suspension thermal noise
- Lower noise electronics, lower noise digitization electronics, improved real time data treatment
- Improved environmental noise monitoring
- Newtonian noise cancelation
- More precise calibration systems
- Development of new strategies for technical noise reduction and noise decoupling

- Continue Virgo's science programme in the LVK gravitational-wave detector network
- Push the potential of the existing infrastructure to its limits
- Test the technologies used in the ET avoiding design mistakes and accelerating commissioning
- Fill a potential gap of a decade between the end of O5 and the first ET design sensitivity
- Keep and develop the expertise of the experimental and data analysis community
- Ensure smooth generational transition and training of new leaders

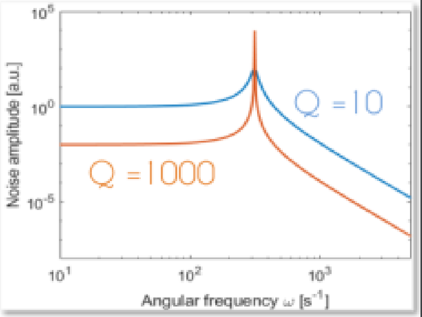
Bragg reflectors of GW interferometers

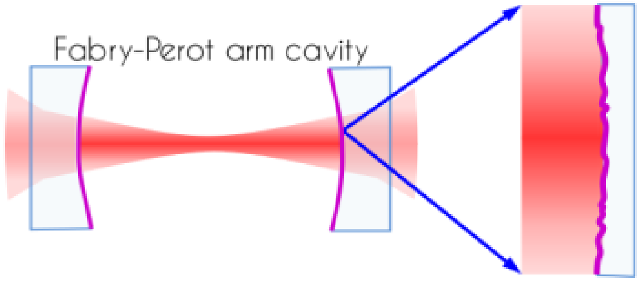


outstanding optical properties
but source of
thermal noise (TN)

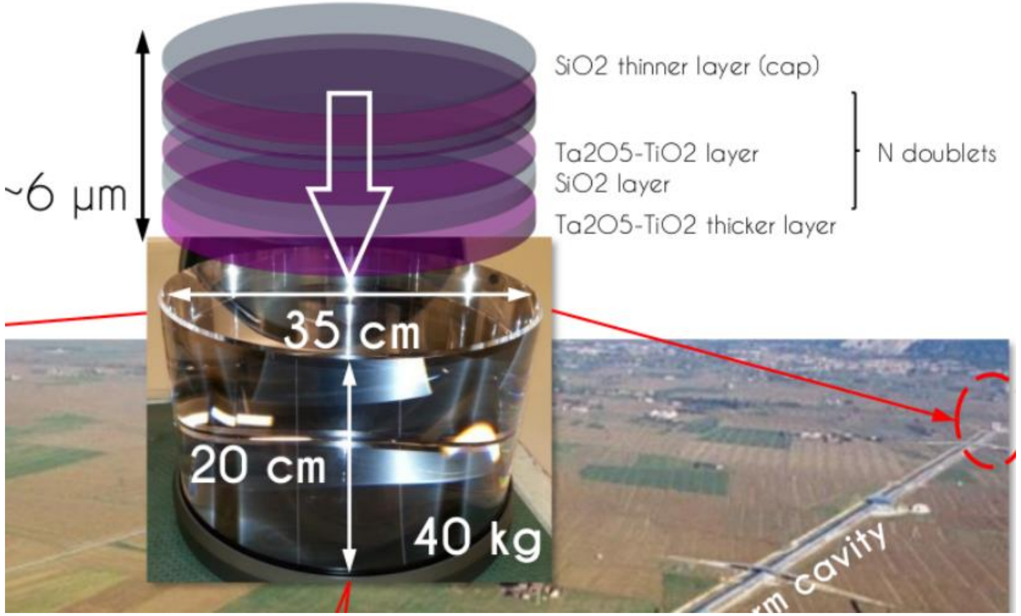
- feature of dissipative systems at thermal equilibrium
- energy leakage to off-resonance spectrum
- intensity proportional to system internal friction

loss angle $\Phi = 1/Q$





surface fluctuations
→ phase noise



Project Supervisor Board
Convener: G. Gemme
EGO director
Virgo Spokesperson
Project Leader
Technical Manager
System Engineer
Commissioning coordinator
Operations coordinator
3 Country representatives

EGO consortium

Virgo Steering Committee

AdV+ Management Team
Project Leader: R. Flaminio
CC: F. Sorrentino, TM: H. Heitmann, SE: F. Carbognani
ITF: C. Buy, SUM: H. Vocca, ESC: M. Was, ENV: R. Passaquieti, QNR: J.P. Zendri

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- **PSL** W. Chaibi
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- **SLC** L. Mir
- **DET** R. Gouaty
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- **EMS** R. De Rosa

QNR
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- **SVS** F. Sorrentino
- **SIN** R. Bonnand
- **FLT** A. Bertolini

1. Target

- Goal: delivered a HR stack (T=4-5ppm @1064 nm) with low optical losses and low CTN with Ti-GeO2/SiO2 stack
    - Absorption <1 ppm
    - Scattering< 10 ppm
    - CTN reduced by a factor 2 versus Advanced VIRGO coating (Ti-Ta2O5/SiO2)
    - Uniformity : same as AdV VIRGO/LIGO Test Mass

Deliverable: HR ETM Stack coated on a pathfinder (AdV LiGO Test mass scale 1) in the GC