Status of Advanced Virgo and upgrades before next observing runs

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Outline

- **Advanced Virgo design**
- **First direct detection of Gravitational Waves**
- **Advanced Virgo in the last observing run O3**
- **Current upgrade before next observing runs O4,O5: Advanced Virgo+**
- **Conclusions and perspectives**

Virgo Collaboration

Born under joint collaboration Italian INFN and France CNRS today is wider collaboration: 543 members, 104 institutes, 13 countries

ITALY:
INFN & Univ. Roma La Sapienza
INFN & Univ. Roma Tor Vergata
INFN & Univ. Roma Tre
INFN & Univ. Pisa, INFN Genova
INFN & Univ. Napoli
INFN & Univ. Perugia
INFN & Univ. Padova/Trento
INFN & Univ. Firenze/Urbino
INFN Salerno & Univ. Sannio
INFN Milano Bic./Parma/Torino
EGO, INAF

GREECE:
Aristotle Univ. Thessaloniki,
Nat. Kapodistrian Univ. Athens

FRANCE:
APC Paris, LKB Paris, Artemis Nice
LAL Orsay ESPCI, LMA & Univ. Lyon
LAPP Annecy Univ. Grenoble, Navier
GIPSA-LAB, L2IT & Univ. Toulouse
Univ. Rennes, Univ. Strasbourg
Univ. Paris-Saclay

MONACO: Centre Sc. Monaco

BELGIUM:
Univ. Liege, Univ. Cath. Louvain,
Univ. libre Bruxxelles, Univ. Gent,
Univ. Antwerpen, Univ. Vrije Brussell

PORTUGAL:
Ist. Sup. Tec. Lisboa

SPAIN:
IFAE, ICREA Barcelona,
Univ. Barcelona, Univ. Valencia
& Obs. Astronomic

NETHERLANDS:
NIKHEF Amsterdam, Delta Inst.
GRAPPA Univ. Amsterdam
GRASP Univ. Utrecht, Maastricht Univ.
Lorentz Inst. Leiden Univ.
Van Swinderen Inst. Univ. Groningen
IMAPP Radbound Univ.

GERMANY:
Univ. Jena, Max Planck Inst. (AEI)
Institut für Kernphysik

JAPAN: NAOJ

POLAND:
IMPAN Inst. Maths. Warsaw, Univ. Bialystok
Univ. Cracow & CYFRONET
National Center for Nuclear Research

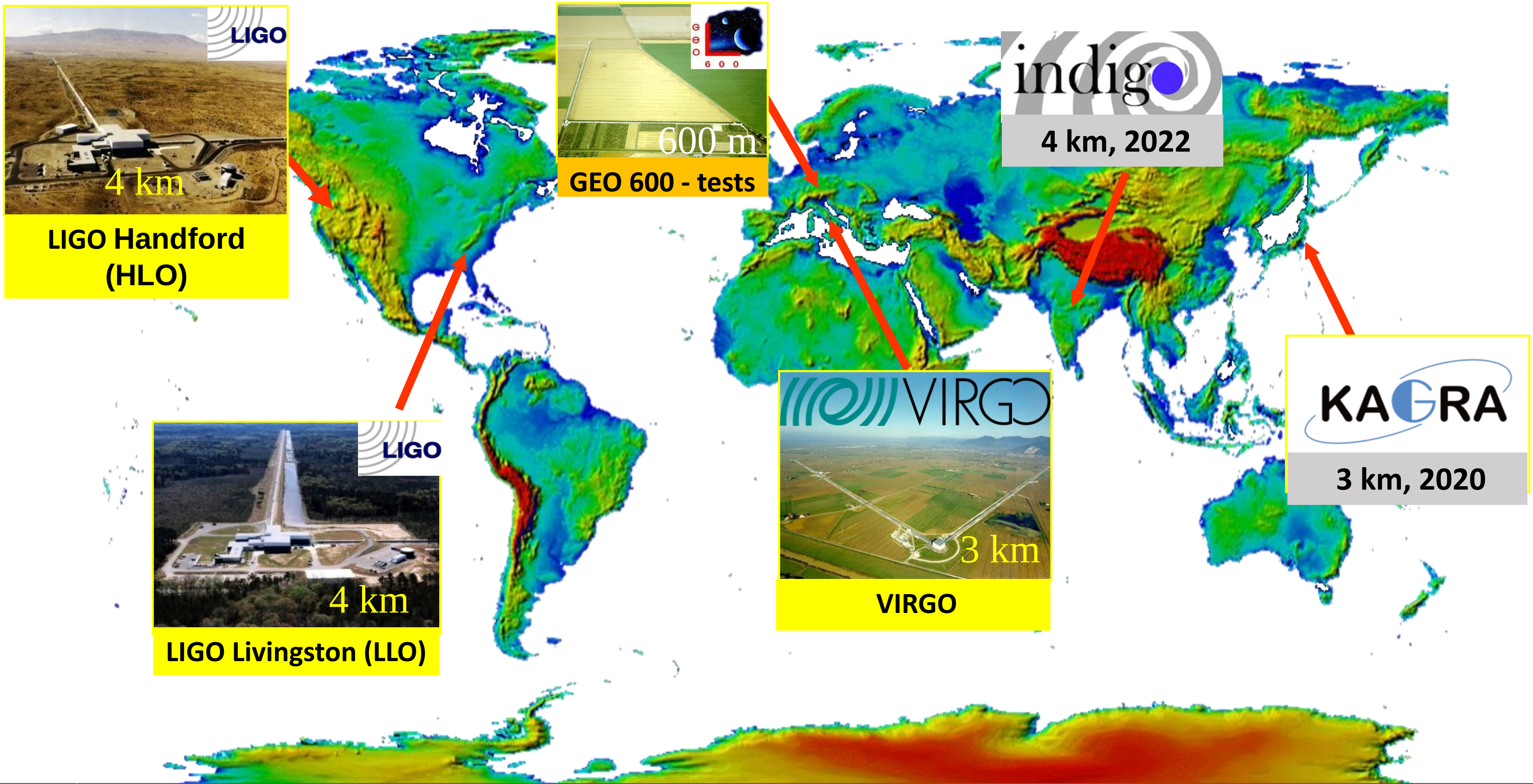
HUNGARY:
Wigner RMKI Budapest, Institute for Nuclear Research, Hung. Academy of Sciences

IRELAND: UCD School of Math. Stats.

https://apps.virgo-gw.eu/vmd/public/institutions

Advanced Virgo project has been formally completed on July 31, 2017.
AdV is part of the international network of 2nd generation detectors. AdV joined the O2 run on August 1, 2017.
O3 started April 1, 2019 till 27 March 2020. Upgrade of AdV started in April 2020

GW detectors worldwide network growing up since 1992



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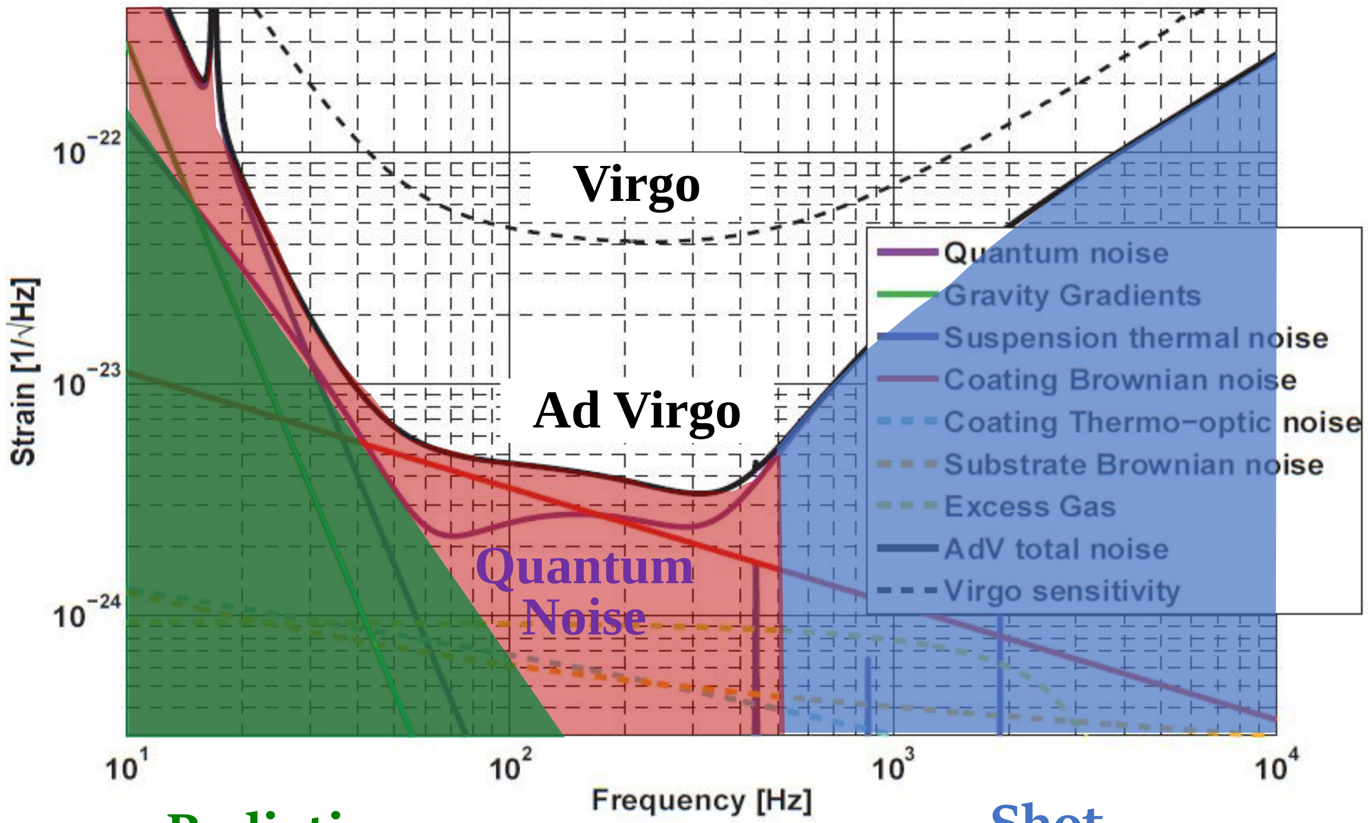
Compared to starting Virgo:

Sensitivity 10 times higher → Detection Rate 1000 times higher

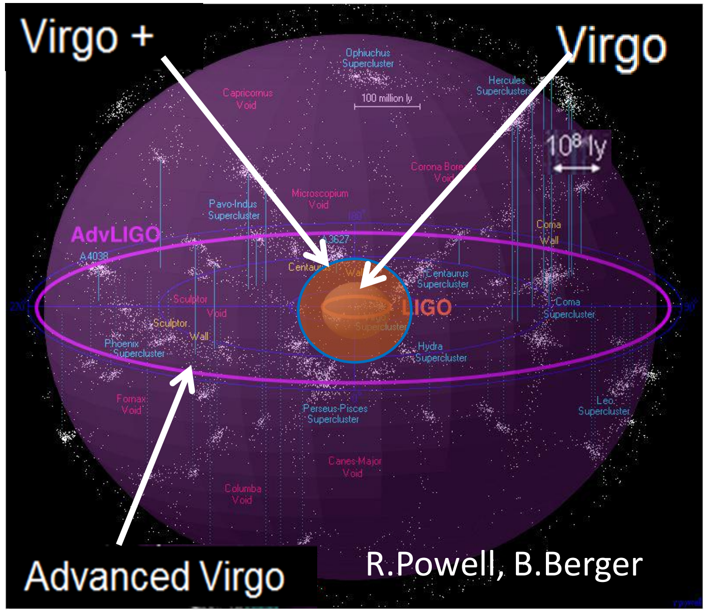
AdVirgo Sensitivity Curve



Radiation Pressure Noise

Thermal Noise

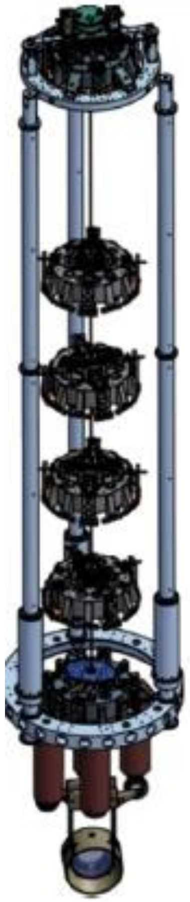
Shot Noise



Main Upgrades

- Heavier mirror mass: 20 kg → 42 kg
- Fabry Perot cavities geometry
- New Payloads with Compensation Plate
- Thermal Compensation System
- Higher Laser Power: 20 W → 60 W

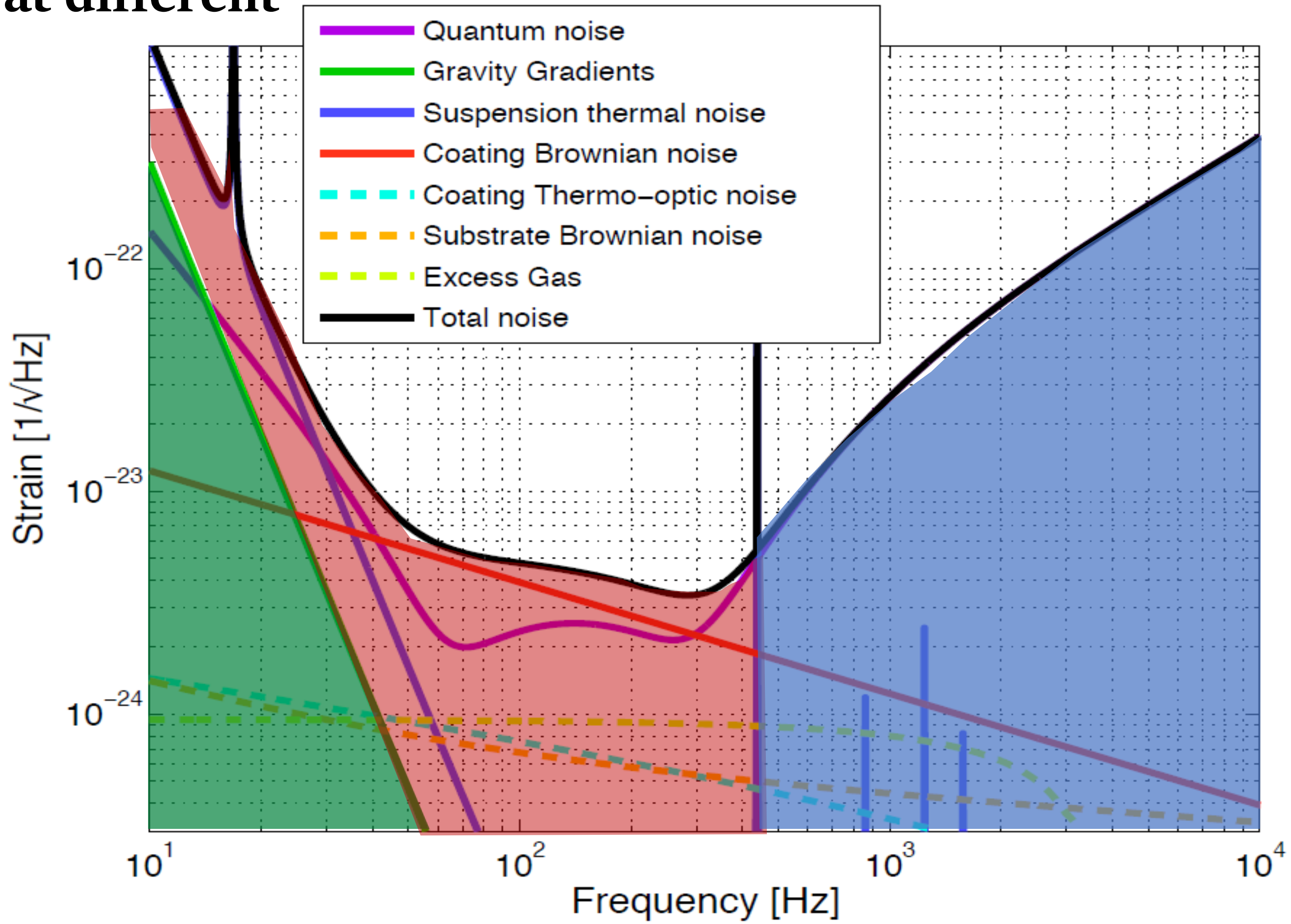
Advanced Virgo design



Limiting noises at different frequencies

Low frequency: seismic noise, Newtonian noise, technical noise

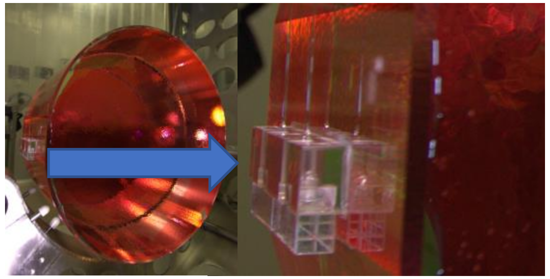
Super Attenuator (SA): attenuation of 10^{11} @10Hz



High frequency: Quantum Shot Noise

High Finesse, high laser power, Frequency Independent Squeezing

Mid frequency: Thermal noise of the mirrors, of the coatings of the suspensions



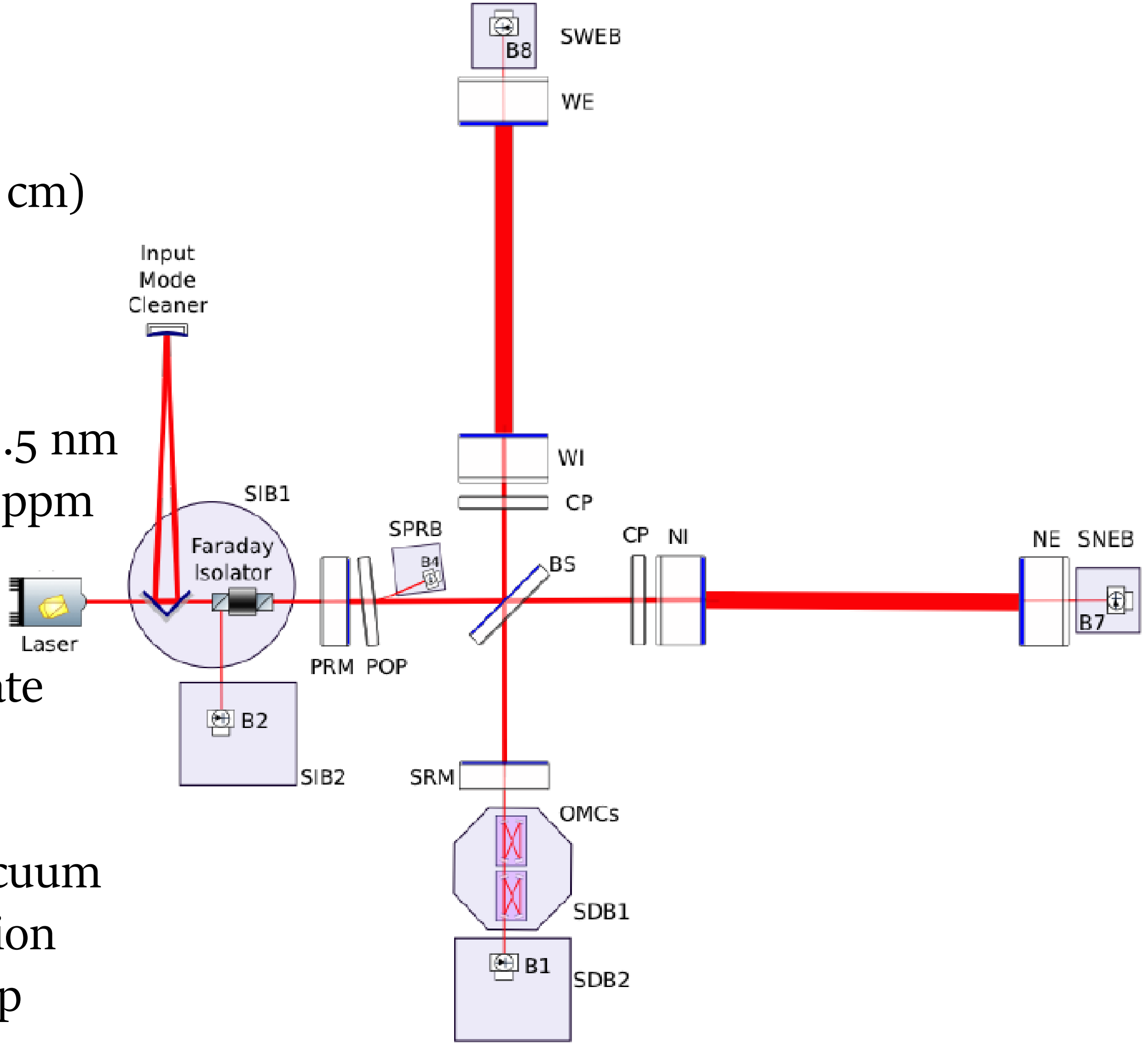
Monolithic suspension

Larger beams, better coatings, better optics quality, Thermal Compensation System

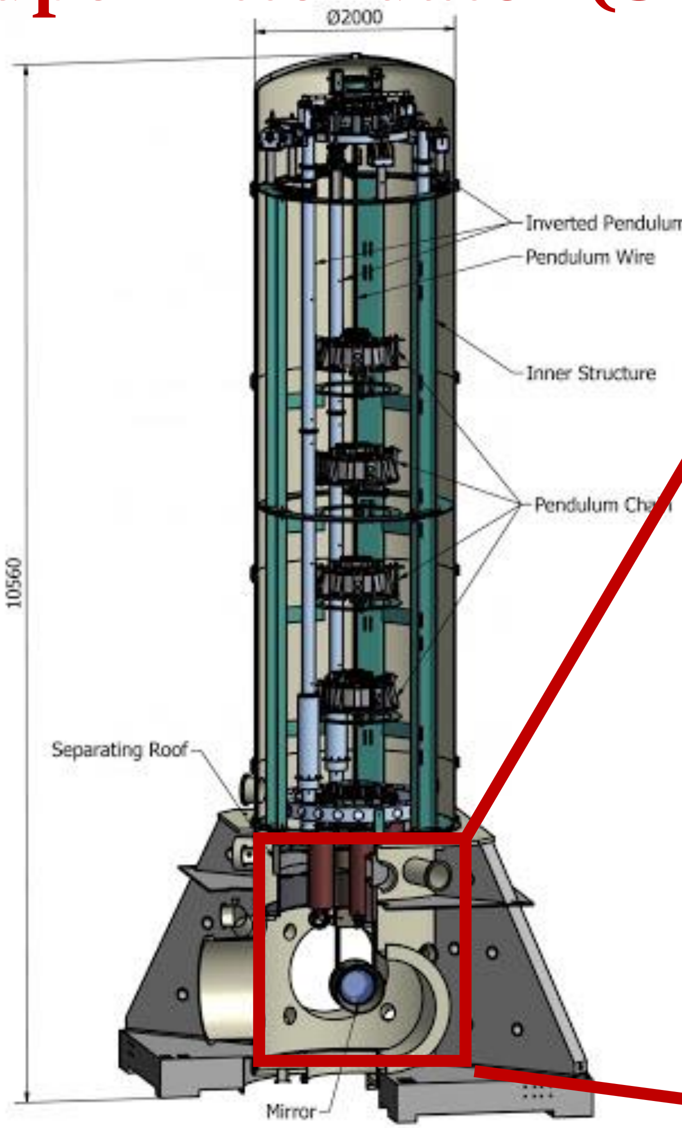
Advanced Virgo design

Instrument improvements before run O2:

- **Heavier mirrors**: 20 kg → 42 kg
- **Larger beam**: 2.5 times larger at ITMs (2.4 cm → 6 cm)
- **Higher finesse:** 3 times than in Virgo+ (150 → 450)
- **Higher Laser Power**: 20 W → 60 W
- Higher power circulating inside arm cavities
- **Higher quality of the optics**: residual roughness <0.5 nm
- Improved coatings to reduce losses: absorption <0.5 ppm scattering <10 ppm
- **Improved vacuum**: 10^{-7} mbar → 10^{-9} mbar
- **Thermal Compensation System** (TCS) to compensate defects of core optics due to laser heating: Ring Heaters, Compensation plate (CP)
- **Straylight control**: suspended optical benches in vacuum (SIB1, SIB2, SDB1, SDB2) for the injection and detection optics and new set of baffles and diaphragms to damp diffuse light

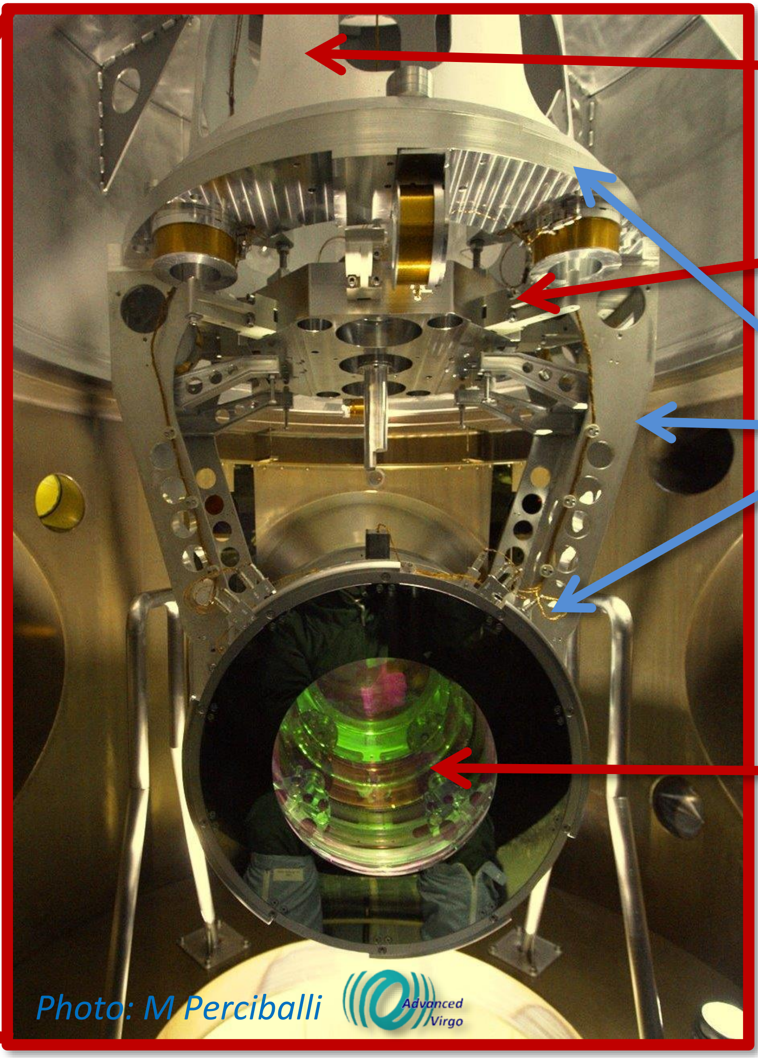


Super Attenuator (SA)



Payload

to SA Filter 7



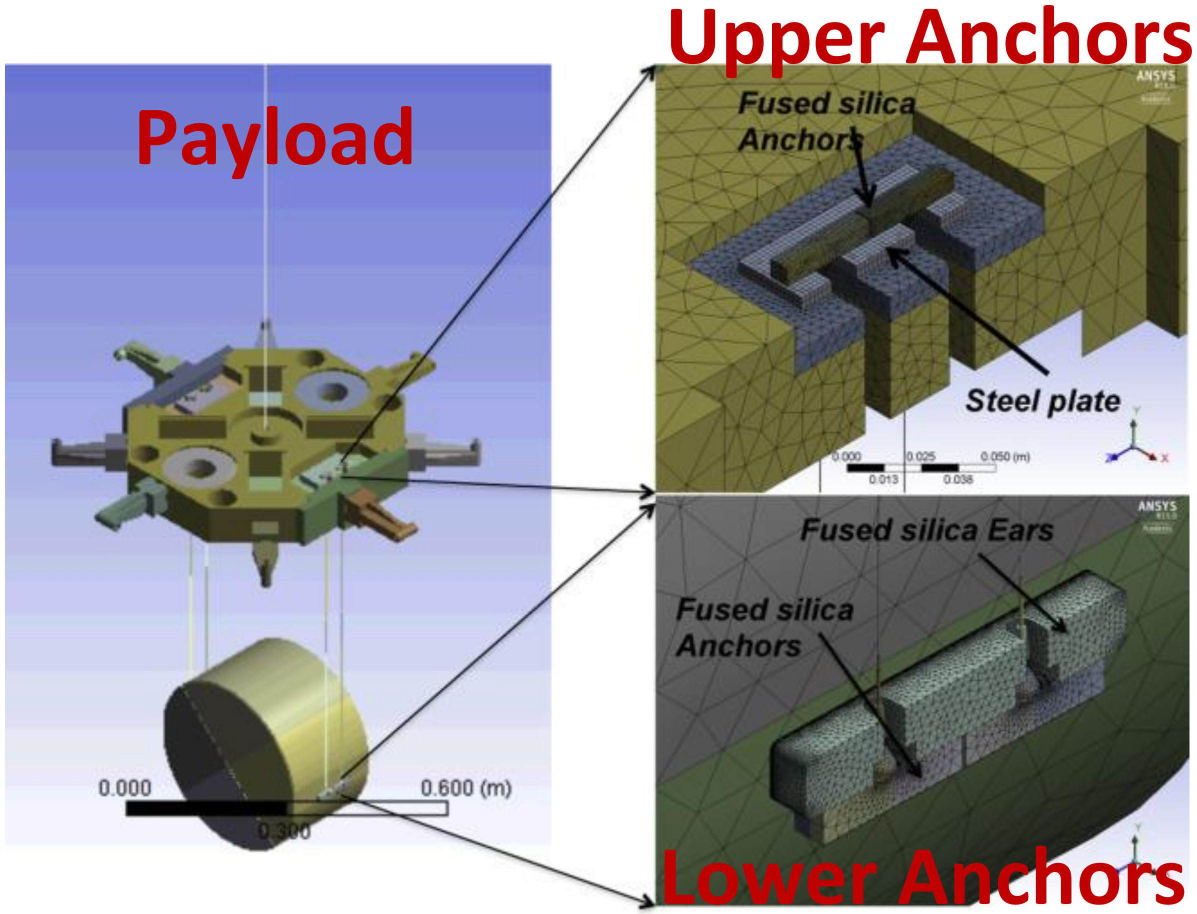
Advanced Virgo design: Monolithic Suspensions

Fused silica (SiO2, same material of the mirrors): 4 fibers for each suspended mirror

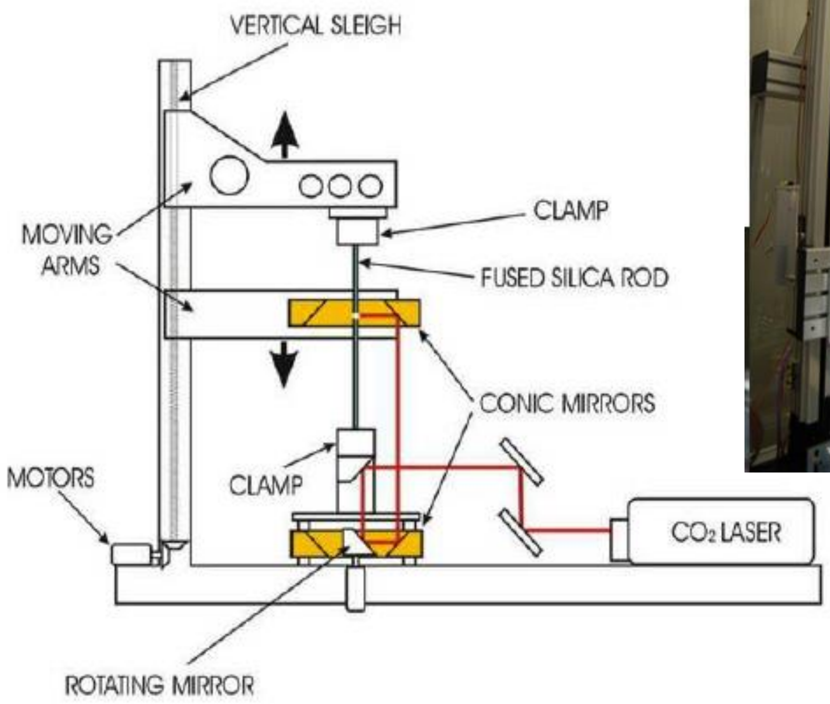
Very low internal mechanical dissipation material (loss angle of the order 10^{-10})

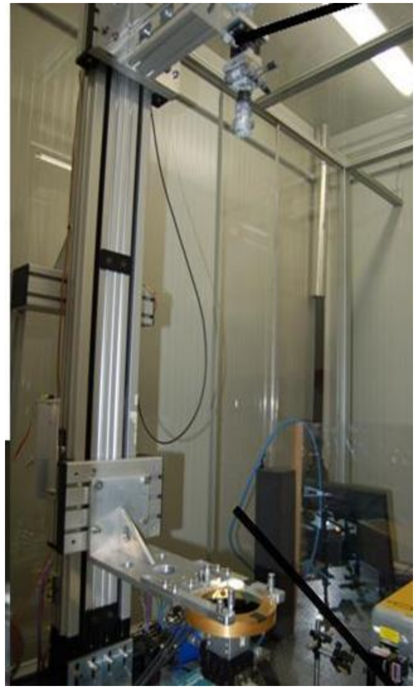
Produced with **CO_2 Laser machine** at EGO: **diameter 400 µm, length 70 cm**

Clamped through upper and lower anchors, then glued via silicate bonding



CO_2 Laser machine for fiber production at EGO

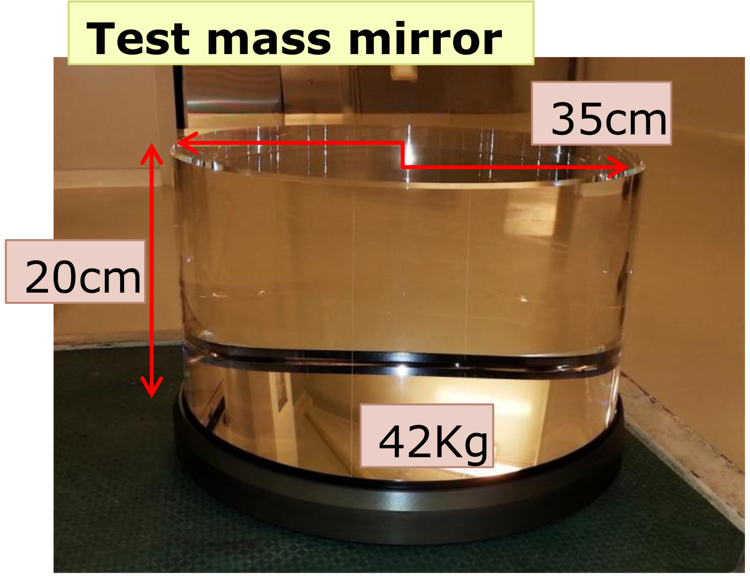


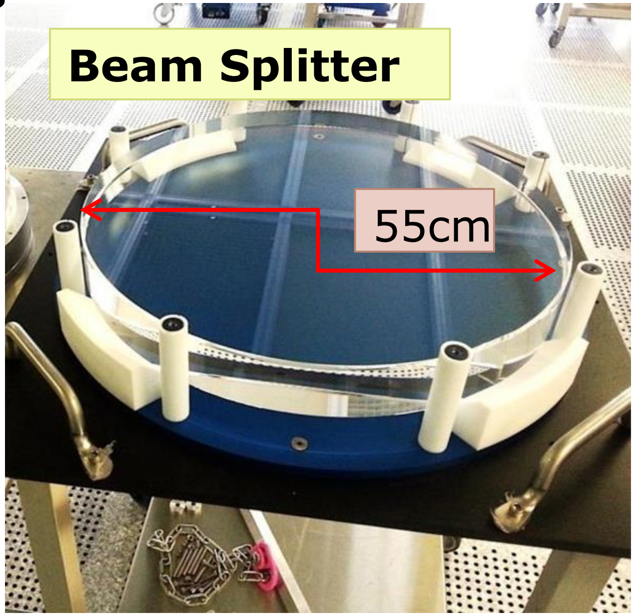


Advanced Virgo Test Masses

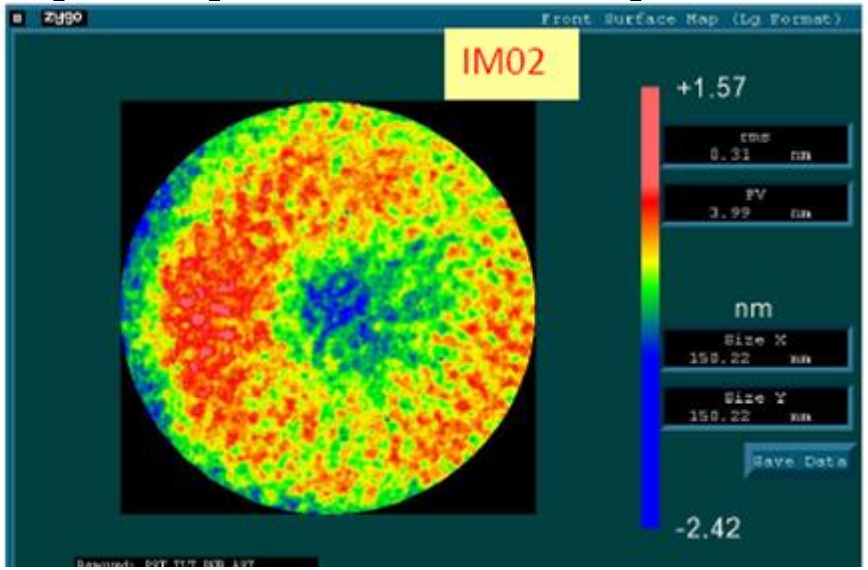
The main optics of Virgo are produced under the supervision of the Laboratoire des Matériaux Avancés (LMA, Lyon)

- **Substrate** by Heraeus (EU) company is made of **Suprasil 3002**: **low light absorbtion** (0.3 ppm/cm) in the NIR (Virgo laser is a Nd:YAG IR of λ 1064 nm) and **high uniformity** ($\Delta n<5\ 10^{-7}$)
- ZYGO (US) company realises the **polishing**
- LMA (Lyon, France) realises the **coatings**





Example of Input mirror surface map after coating



- Heavier mirrors: 20 kg → **42 kg**
- Higher quality of the optics: **residual roughness <0.5 nm**
- Improved coatings to reduce losses: **absorption 0.2ppm, scattering 3ppm**
- Very good AR coating: **32 ppm and 56 ppm of reflectivity**
- End mirrors have reflectivity 99.999% (they let pass only 4 parts per million of the power used to control the ITF performance)
- Input mirros have lower reflectivity (88%)

Advanced Virgo design: Thermal Compensation System

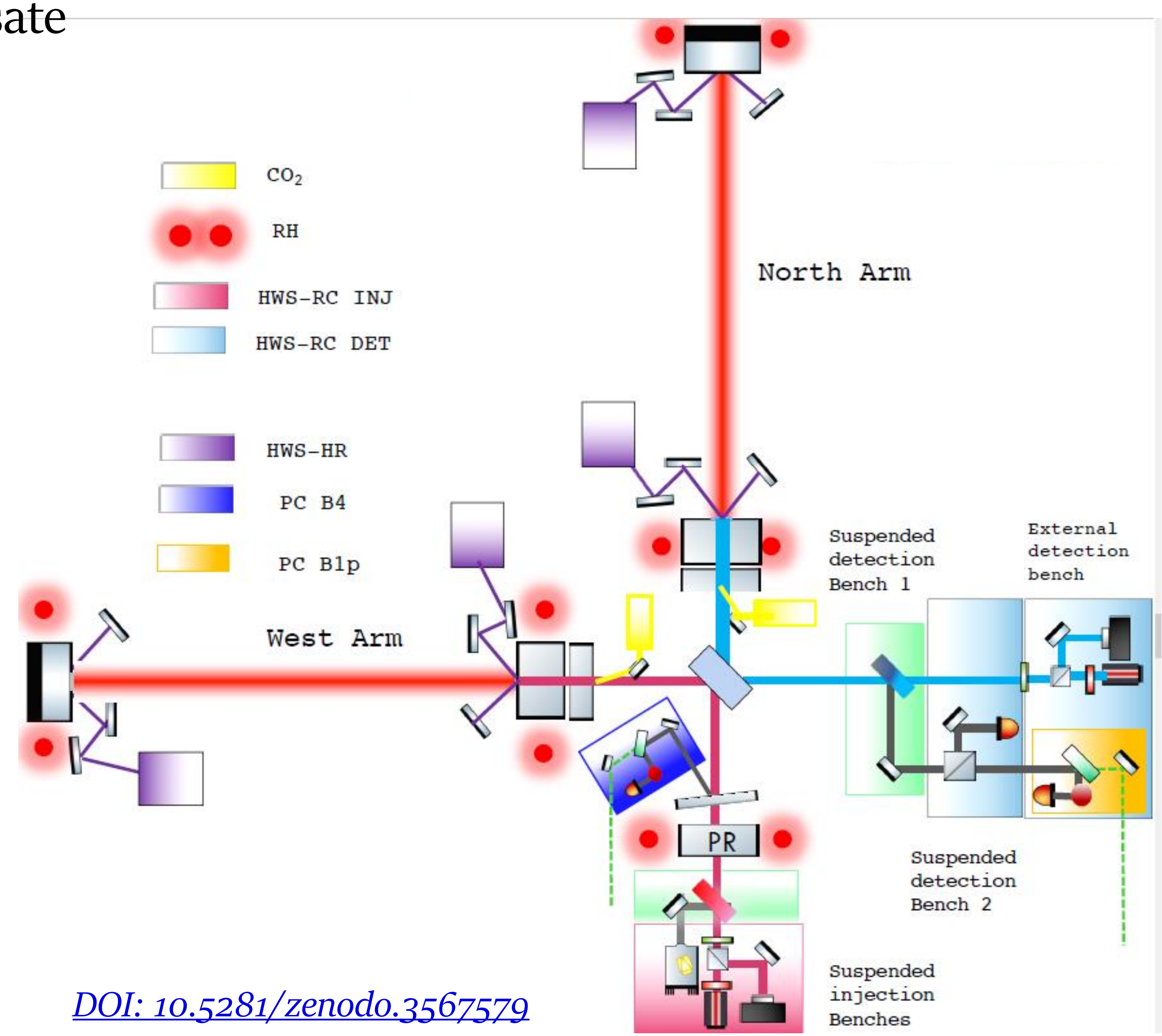
Thermal Compensation System (TCS) to compensate defects of core optics due to laser heating:

TCS actuators

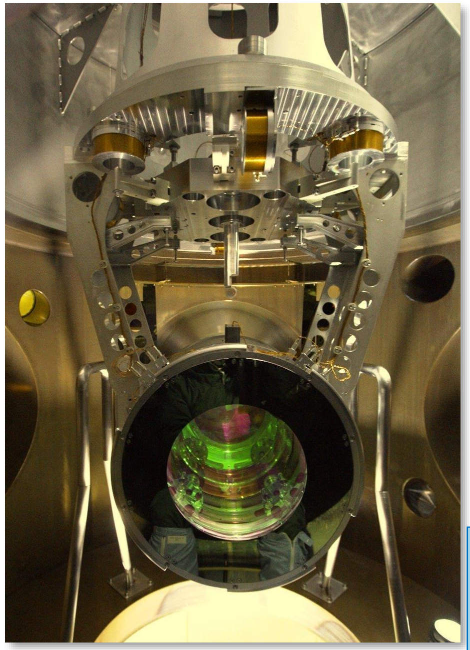
- **Ring Heaters** (RH) act on the thermoelastic deformation of the HR surface
- **CO2 laser** projector corrects thermal lensing

TCS sensors

- **Hartmann Wavefront Sensors** in the recycling cavity (HWS-RC): used to measure the thermal lensing
- **Hartmann Wavefront Sensors** on the HR surface (HWS-HR): used to measure the thermoelastic deformation of the HR surface;
- **Phase cameras** (PC) used to sense independently the carrier and sidebands in the PRC and on the DP



DOI: 10.5281/zenodo.3567579

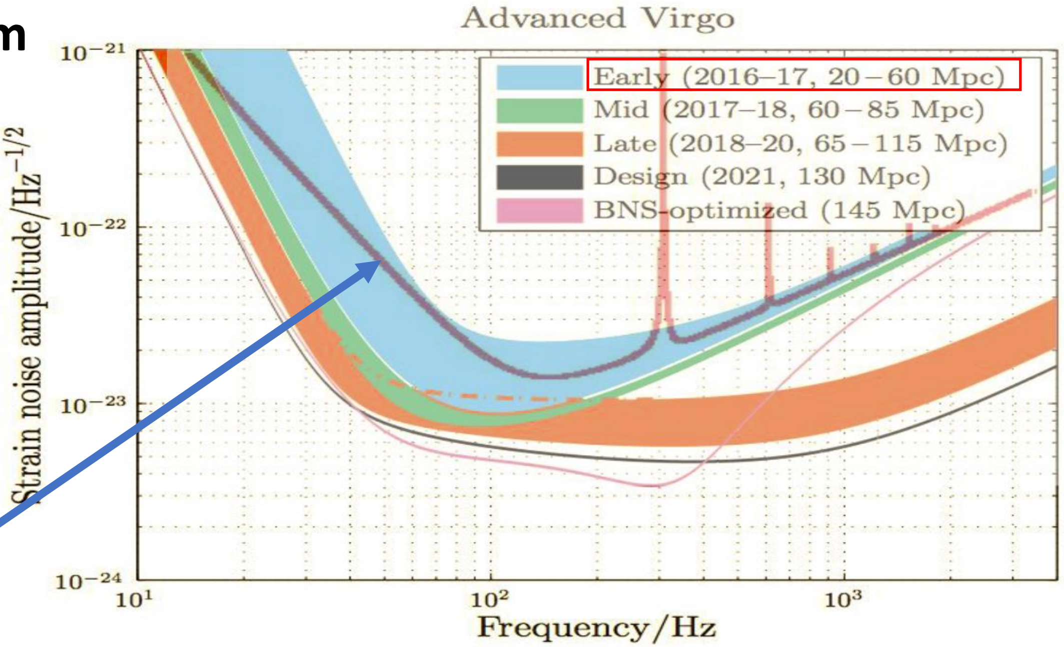


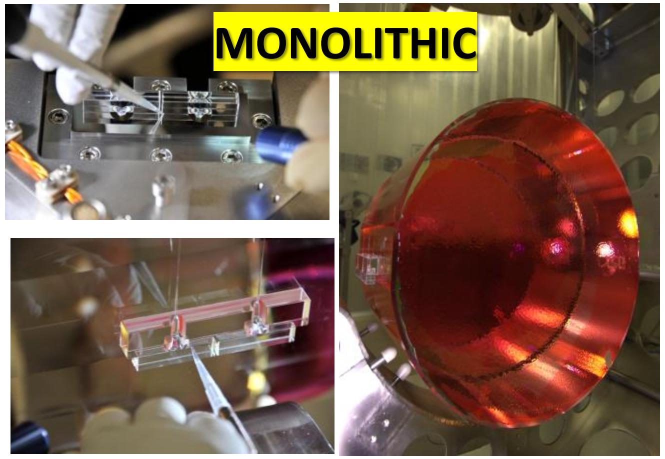
Dust contamination from vacuum system

monolithic susp. failures

Steel-wire backup solution

Sensitivity with steel wires still compatible with the goal for the early phase





Steel ($\phi = 10^{-3}$)

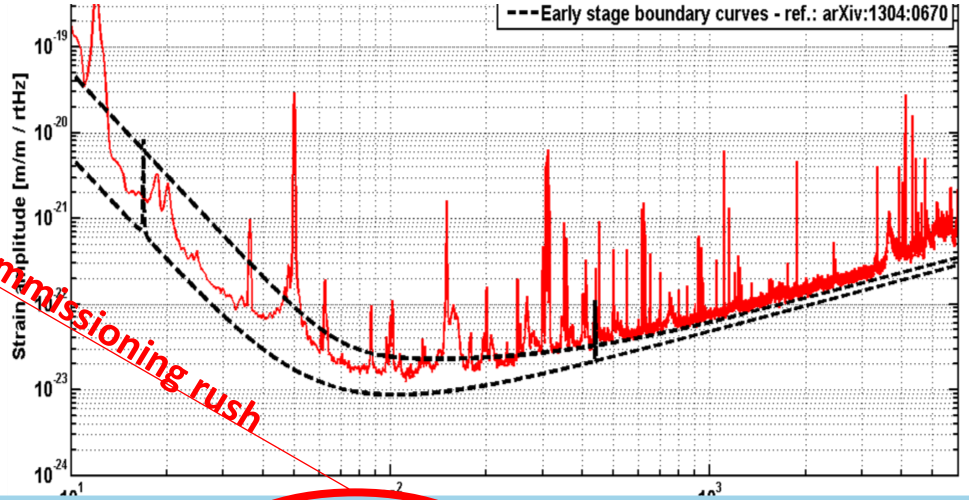
Range NS-NS - 45 Mpc

Range BH-BH - 202 Mpc

Monolithic

Range NS-NS - 101 Mpc

Range BH-BH - 985 Mpc



fast commissioning rush

BNS range ~ 28 Mpc → **ready to join O2!**

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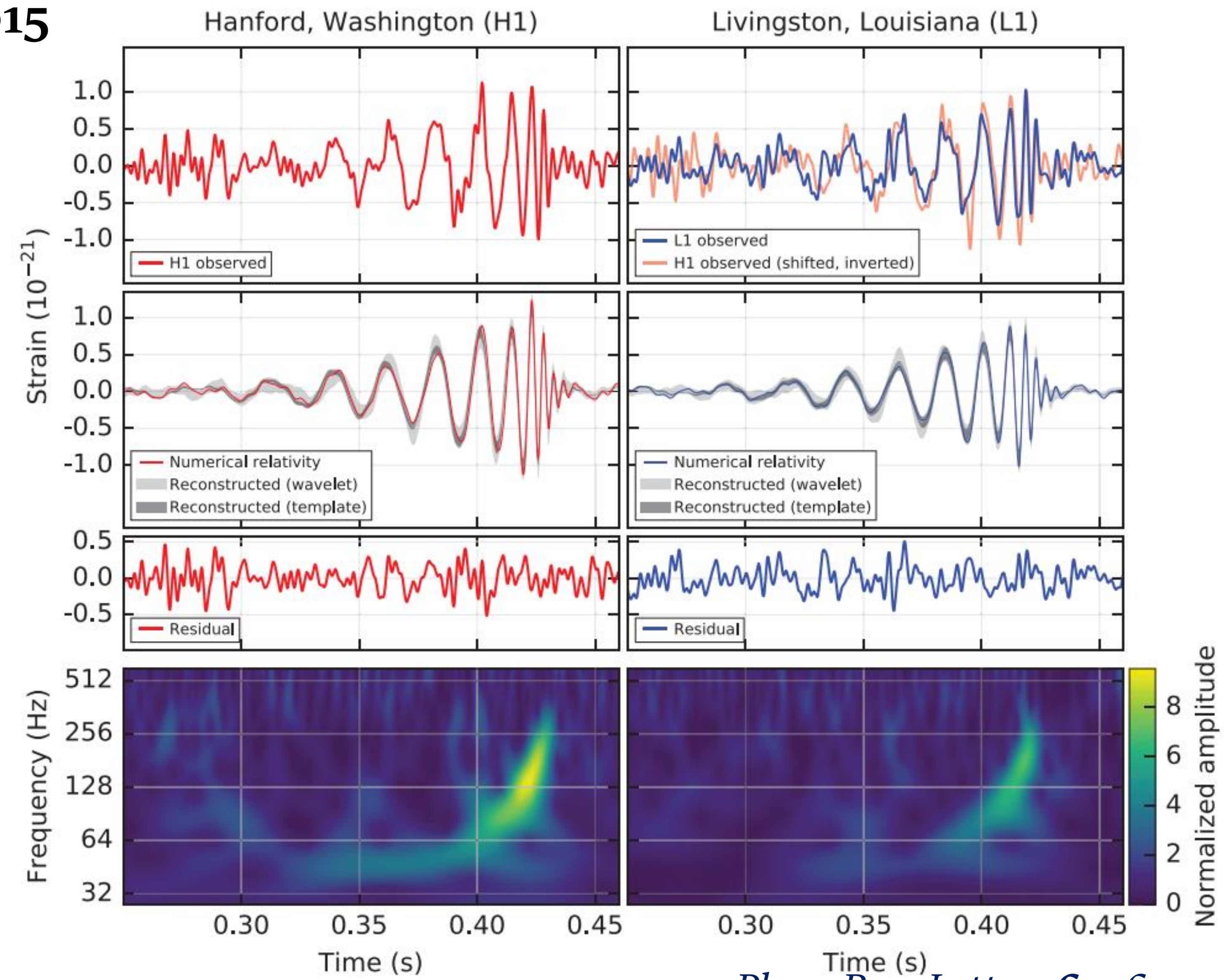
Birth of GW Astronomy

On September 14,2015

GW150914 :
First direct detection of GWs
and first observation of a binary BH merger

Demonstration of the existence of binary stellar-mass BH systems

Special Breakthrough Prize 2016 in fundamental physics to all Virgo and LIGO collaboration



Phys. Rev. Lett. **116**, 061102 (2016)

Source of GW150914

$M_1 = 36\ M_{Sun}$
$M_2 = 29\ M_{Sun}$

$M_{end} = 62\ M_{Sun}$
$E_{GW} = 3\ M_{Sun}c^2$

$D_L = 410\ Mpc$

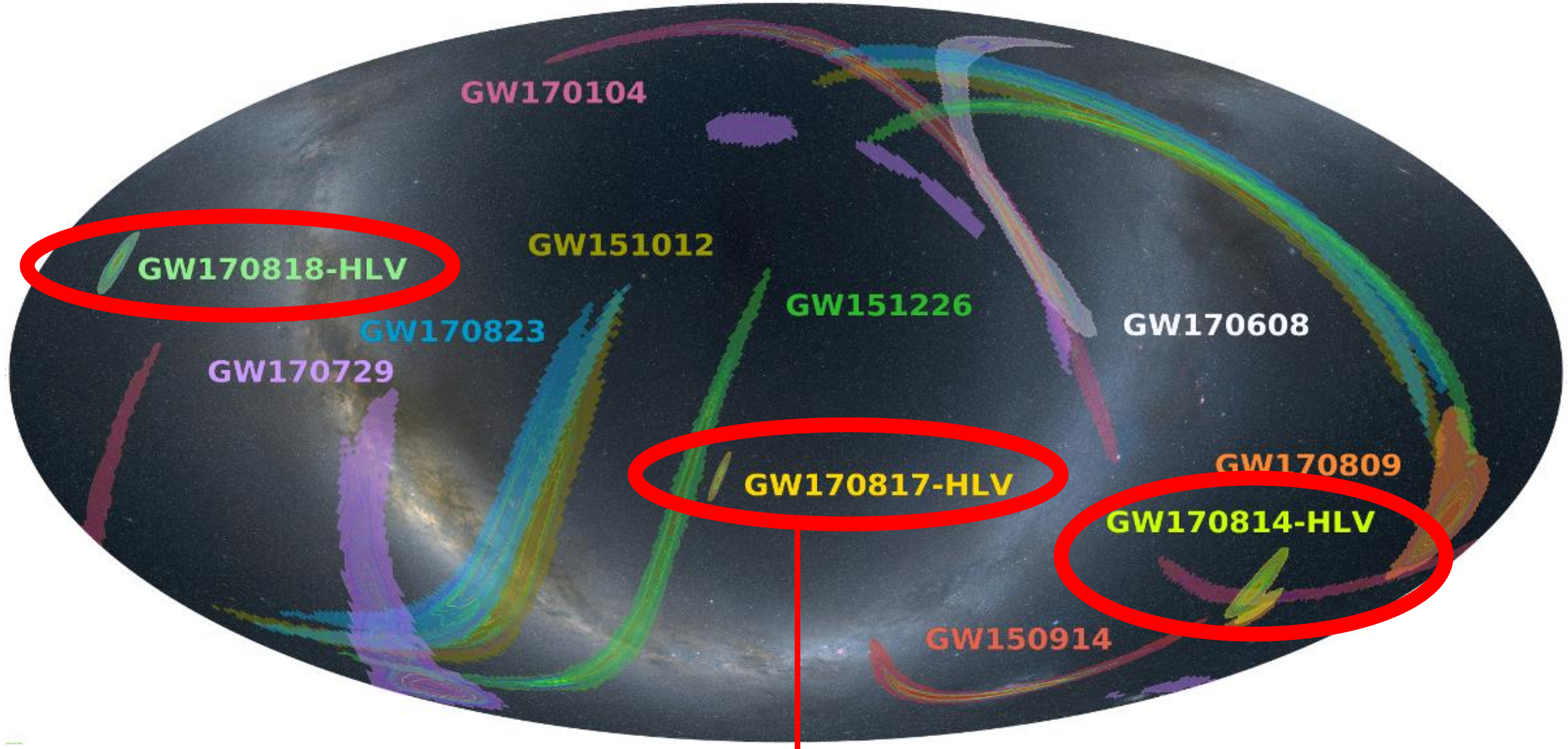
$SNR = 24$

$false\ alarm\ rate \ll \frac{1\text{event}}{203000\text{ yrs}}$

$significance \gg 5.1\ \sigma$

Skymap of detected GWs in O1-O2

With the network of 3 detectors HLV (LLO, LHO and Virgo) better sky localization:
GW170814, GW170817 and GW170818



EVENT	$E_{GW}\ (M_{Sun}c^2)$	D_L (Mpc)	ΔΩ(deg²)
GW150914	3.1	410	182
GW151012	1.6	1080	1523
GW151226	1.0	450	1033
GW170104	2.2	990	921
GW170608	0.9	320	392
GW170729	4.8	2840	1041
GW170809	2.7	1030	308
GW170814	2.7	540	87
GW170817	≥ 0.04	40	16
GW170818	2.7	1060	39
GW170823	3.3	1940	1666

GW170817 first binary NS coalescence: birth of Multimessenger Astronomy

Observed till now: coalescing binaries of BHs and NSs
Still to be observed: SN, isolated NS, stochastic background

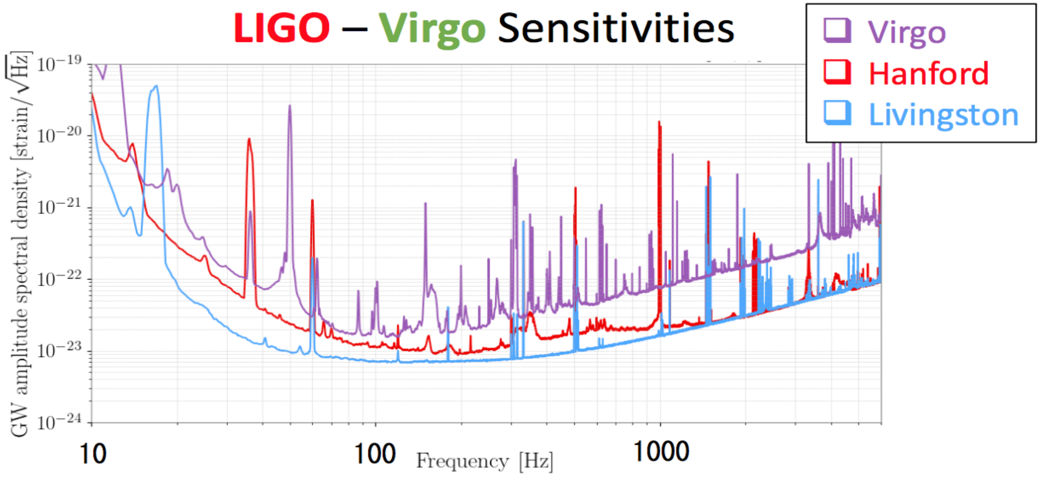
Advanced Virgo in O2

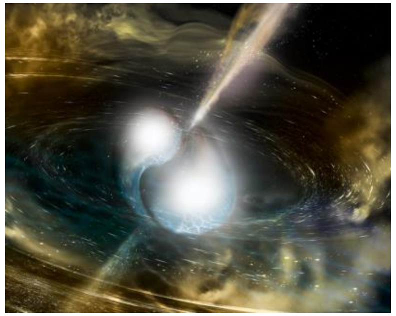
★ **GW170814**
★ **GW170817**

- **O1** ~**49 *days*** of coincident **LIGO** data
- **O2** ~**120 *days*** of coincident **LIGO** data
  ~**16 *days*** of coincidence with **Virgo** data
  10 GW alerts for EM follow-up

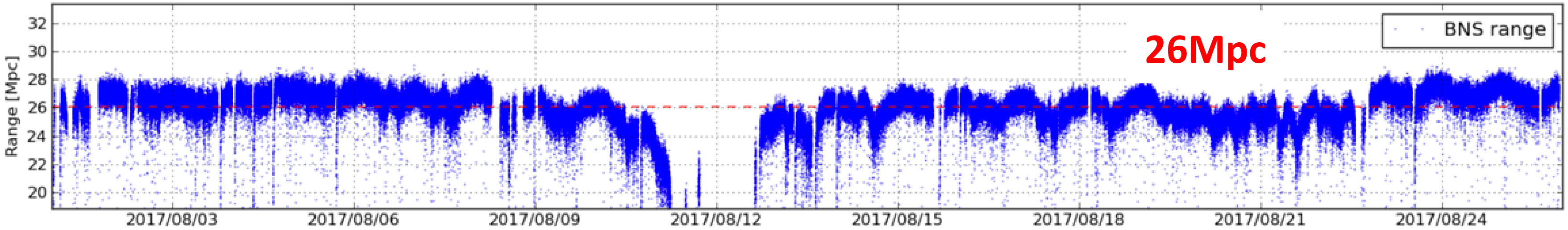
Averaged distances to which Binary Neutron Star could be detected

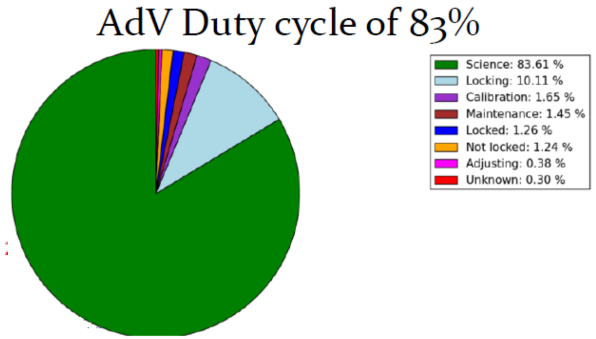
VIRGO : 26 Mpc
HANFORD : 55 Mpc
LIVINGSTON : 100 Mpc





❑ observations 2015-17 vs 2010:
averaged observable volume of Universe : **~100x** gain for **BBH** like GW150914
~30x gain for **BNS** coalescence events





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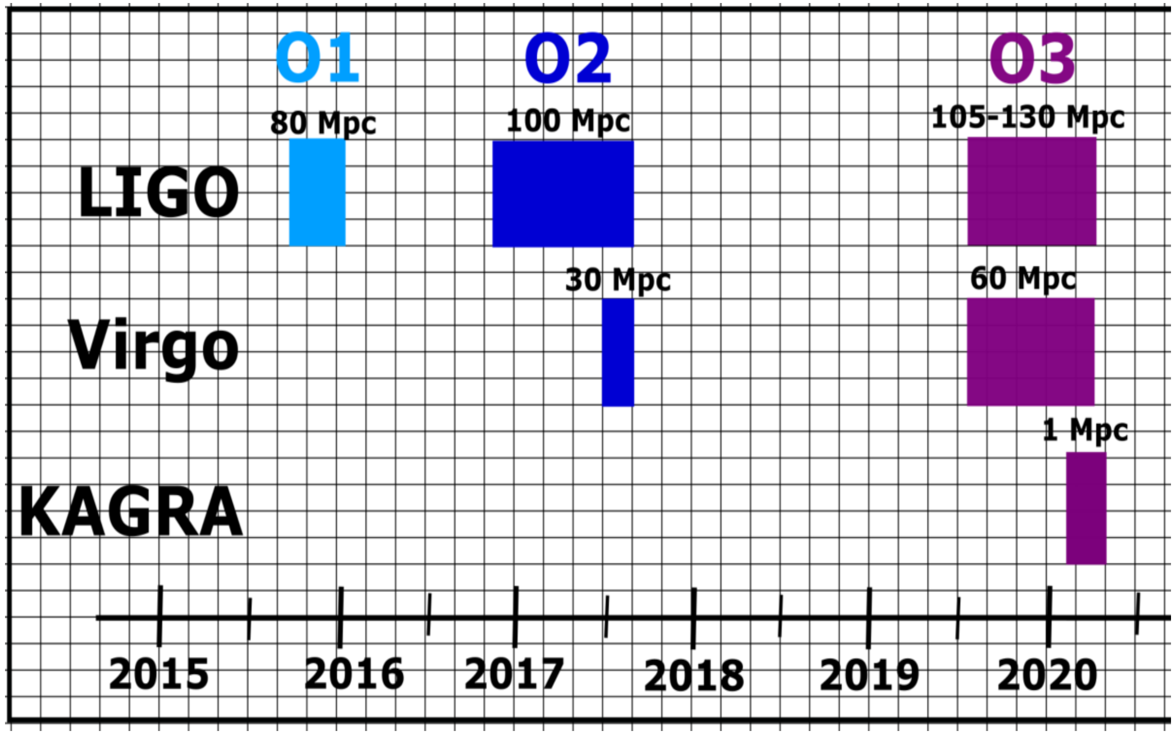
Timeline of Observing Runs and Upgrades: from O1 to O3



O1 = 12 Sept 2015 – 19 Jan 2016 (LIGO)

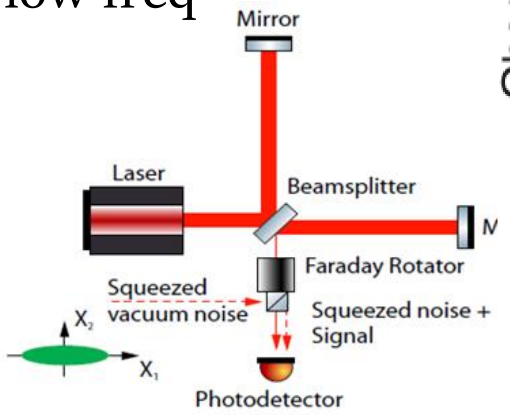
O2 = 30 Nov 2016 – 25 Aug 2017
(Virgo joined 1 Aug 2017)

O3 = 1 Apr 2019 – Mar 2020
(KAGRA initially planned to join the network on Feb 2020, it reached the 1Mpc after the end of LIGO-Virgo O3 and did a short run in Apr 2020)

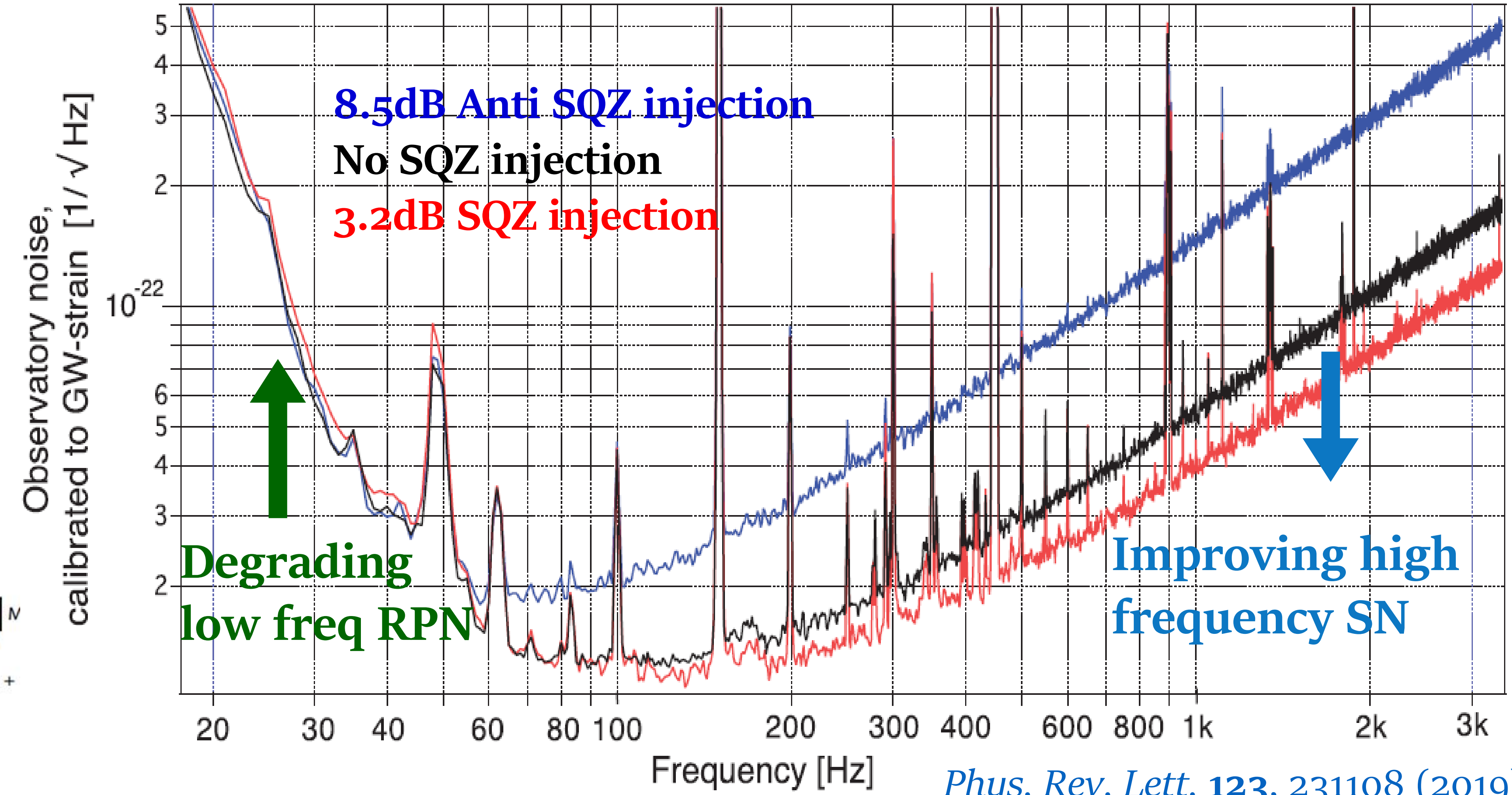
*BNS ranges reached (O1, O2, O3)

O2 → O3 AdV: re-introduction of monolithic suspension; Frequency Independent Squeezing

Injection of **phase squeezed vacuum field** from the **dark port** of the ITF **improves SN** at **high freq** but degrades RPN at low freq



AdVirgo sensitivity improvement in O3: 3.2 dB of FIS



[*Phys. Rev. Lett.* **123**, 231108 (2019)](#)

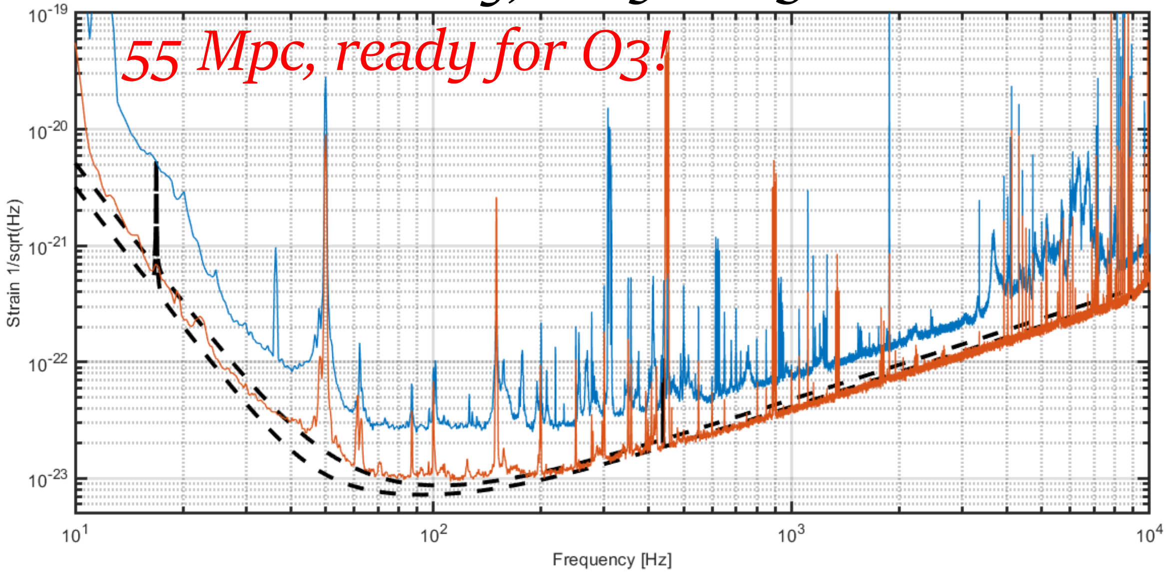
5% - 8% overall sensitivity improvement of the detector (BNS horizon)
16% - 26% BNS detection rate increase

(see V. Sequino's talk)

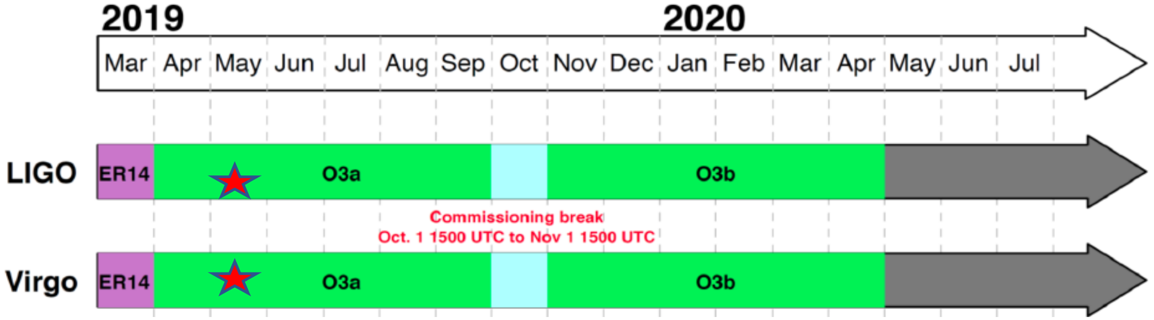
Advanced Virgo sensitivity from O2 to O3

AdV Sensitivity, 2019 Feb 5th :

55 Mpc, ready for O3!



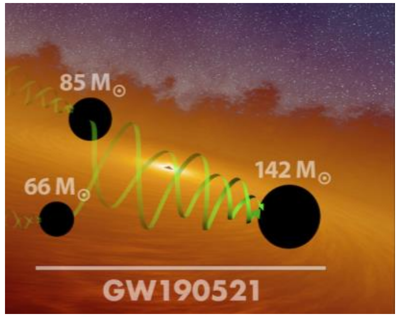
12 months of data taking: Apr 2019 – 27 March 2020

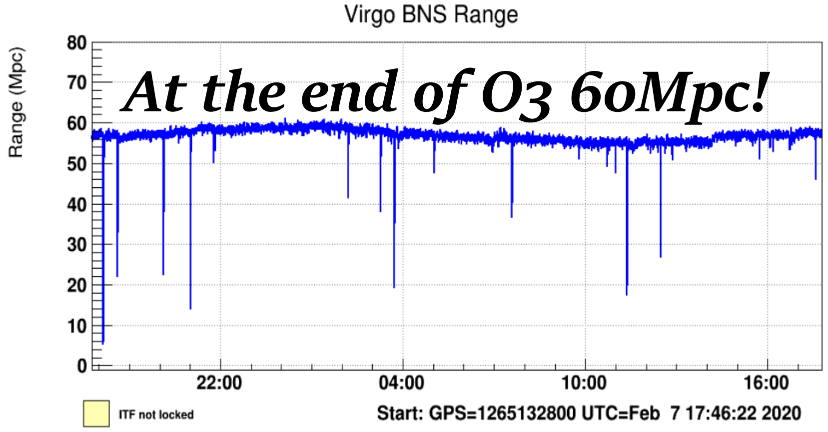


★ **GW190521**

[Phys. Rev. Lett. 125, 101102 (2020)]

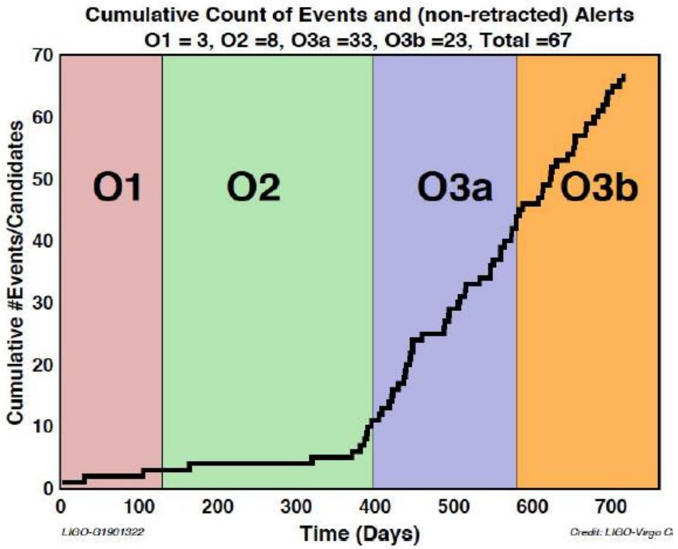
the most massive BH collision observed so far!





AdV duty cycle in O3a and O3b

- Observing 76.3% - 75.6%
- Locked 6.1% - 6.9%
- Not locked 17.7% - 17.5%



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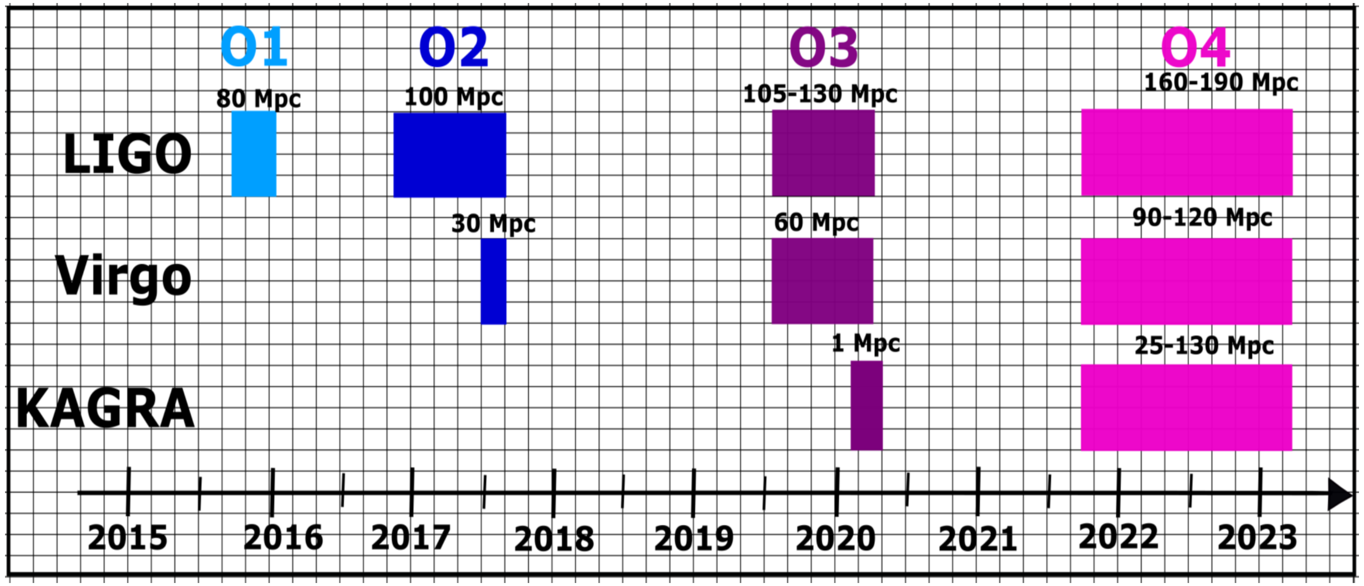
Timeline of Observing Runs and Upgrades

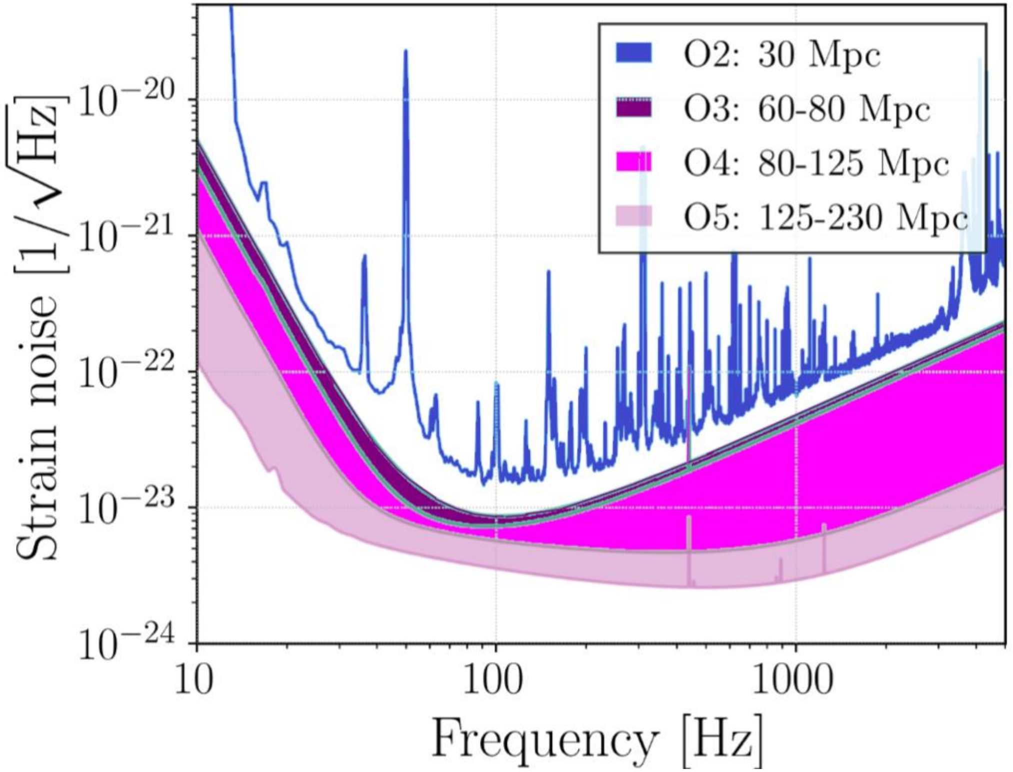
Due to COVID-19 pandemic O3b suspended 27 March 2020
LIGO and Virgo decided to focus on upgrades planned for O4
Two weeks of GEO/KAGRA joint data taking (April 7th - 21st)

O4 foreseen Jan 2022 – mid 2023



*BNS ranges attained (O1, O2, O3) or foreseen (O4)

Advanced Virgo Sensitivity curve



O3 → O4 AdV+ phase I: Signal recycling mirror; Frequency Dependent Squeezing (300m Filter Cavity)

O4 → O5 AdV+ phaseII: Larger mirrors (550 mm diam., 105 kg, End Mirrors), Coating loss reduction, lower CTN using larger beams on the two End Test Mass mirrors

Advanced Virgo +: Phase I

New IMC payload
+
Instrumented baffle

New IMC new mirrors coated and characterized: assembly to be started
Instrumented baffle: R&D done, construction on-going

HVAC noise reduction

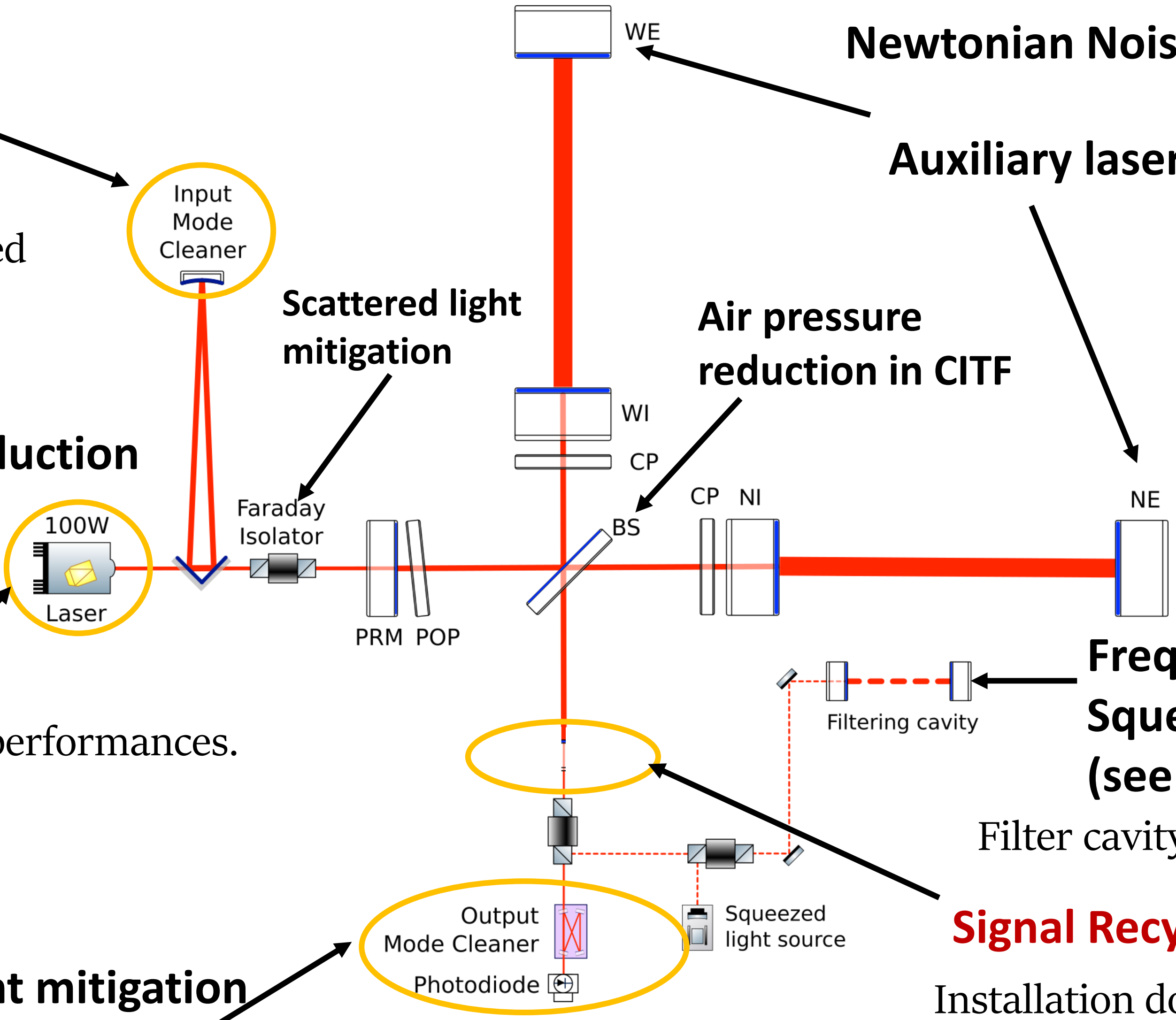
Scattered light mitigation

Air pressure reduction in CITF

Newtonian Noise cancellation

Auxiliary lasers

Network of sensors inside and outside the buildings to test new methods of noise subtraction



Laser Upgrade (125 W)

New fiber laser 125 W. Good noise performances.
Installation started mid July 2020

Frequency Dependent Squeezing (FDS)
(see V. Sequino's talk)

Filter cavity infrastructure completed

New OMC
Scattered light mitigation
New photodiode electronics

Signal Recycling mirror

Installation done in July 2020
(see next slide)

Signal Recycling Mirror (SR)

Advanced Virgo+ will be a **dual recycled ITF**: Power Recycling (PR) + Signal Recycling (SR) cavities.

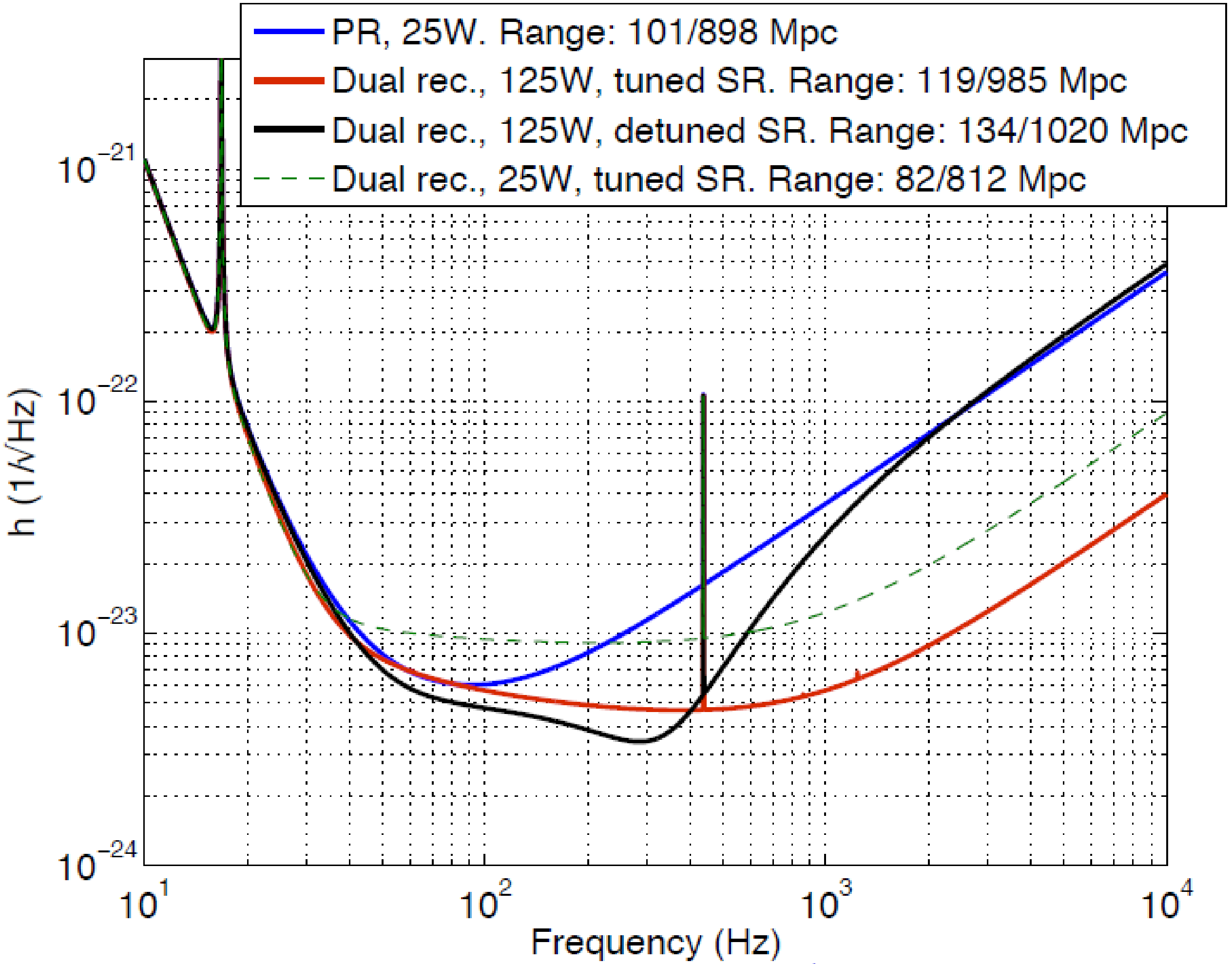
Tuning SR parameter changes the shape of the sensitivity curve optimizing it for different astrophysical sources

AdV detector is tunable in three ways:

- by changing the laser power
- by changing the transmissivity of the SR mirror
  → this influences the detector **bandwidth**
- by tuning the position of the SR mirror
  → this changes the **freq. of max. sensitivity**

In the plot are shown 4 different operation modes:

- **power recycled, 25 W** no SR (blue curve)
- **dual recycled, 125 W**, wideband SR tuning (red curve)
- **dual recycled, 125 W,** detuned SR optimized for BNS inspiral range (black curve)
- **dual recycled, 25 W,** tuned SR (green dashed curve)

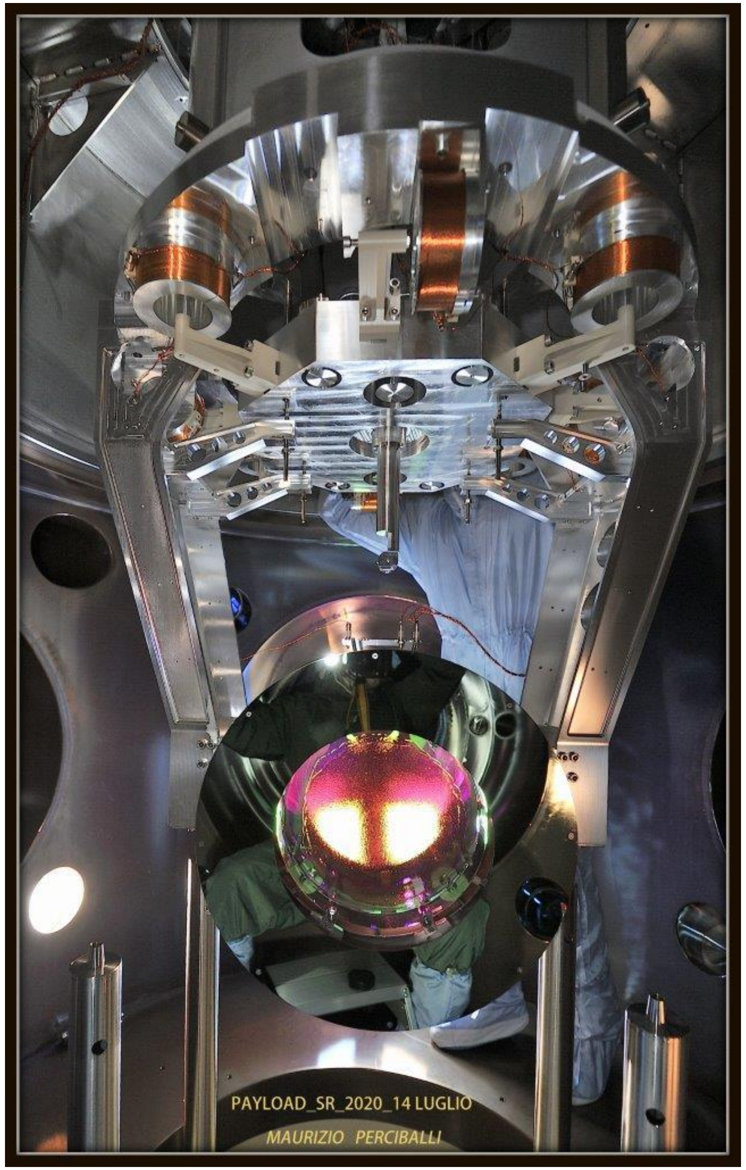


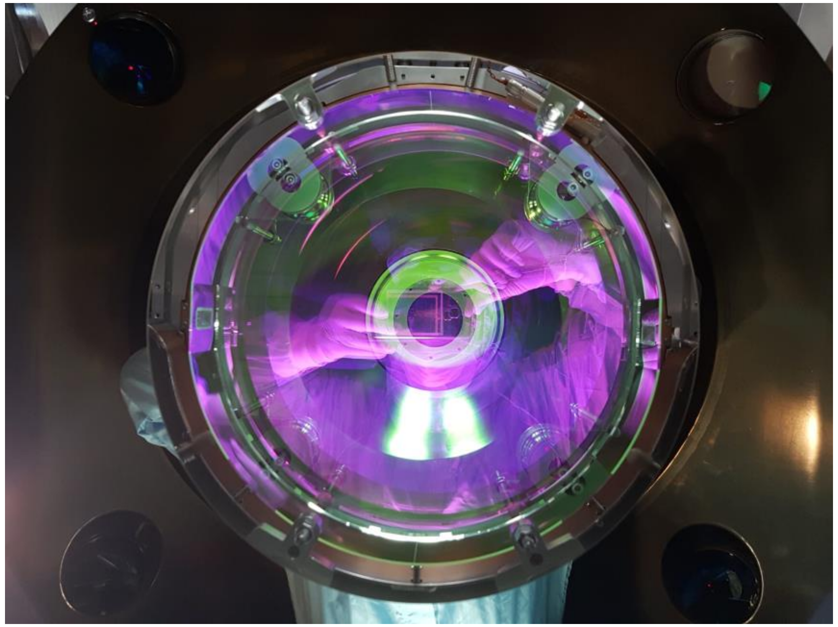
In the legend are reported in Mpc the inspiral ranges for BNS and BBH (BH of 30 Msun).

AdV TDR : VIR-0128A-12

Signal Recycling Mirror (SR) installed

SR installed in tower July 2020





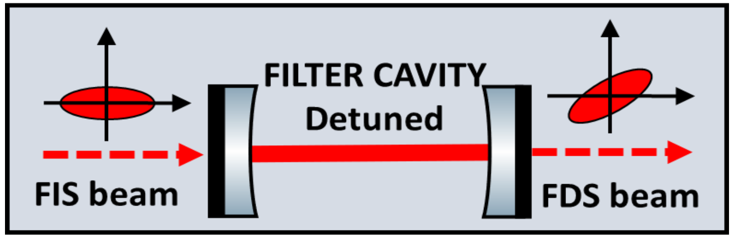
detail of the SR mirror after first contact protection was removed

credits M. Perciballi

Filter Cavity (FC) in Advanced Virgo +

Detuned Fabry Pérot cavity has a frequency dependent response:

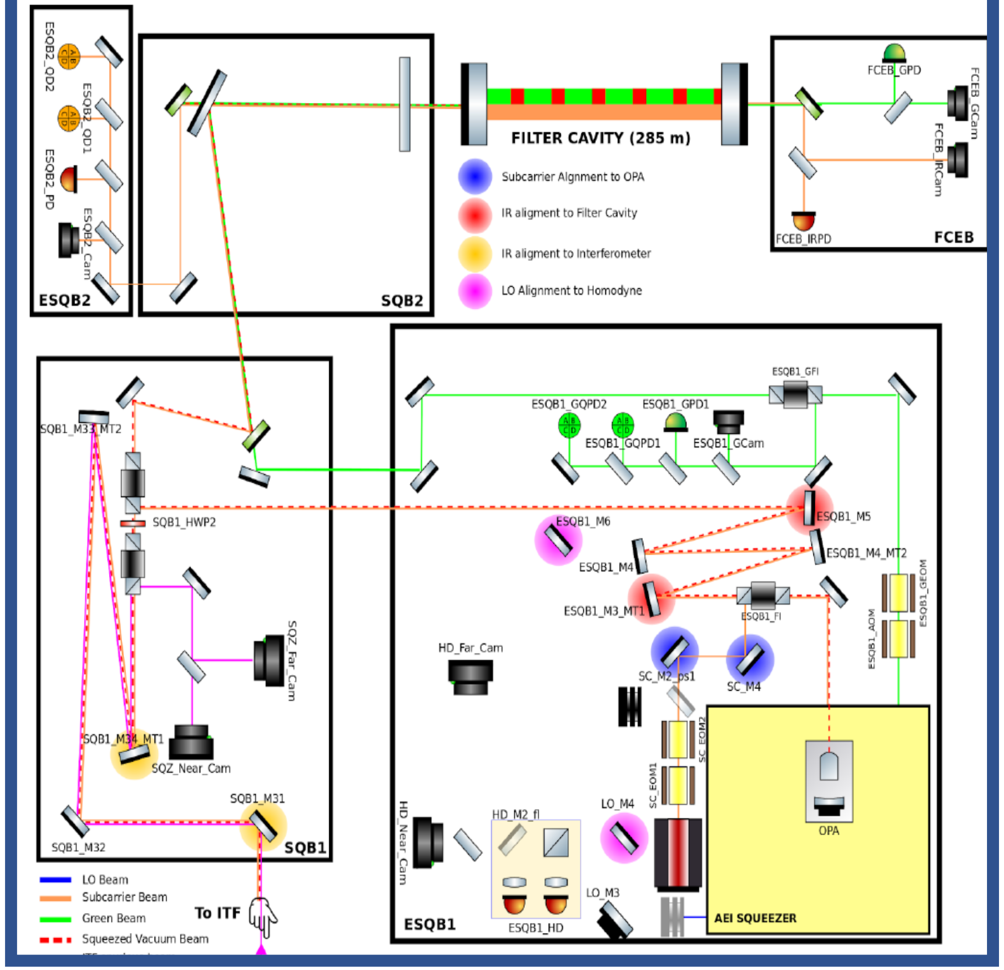
Rotation induced at a frequency Ω



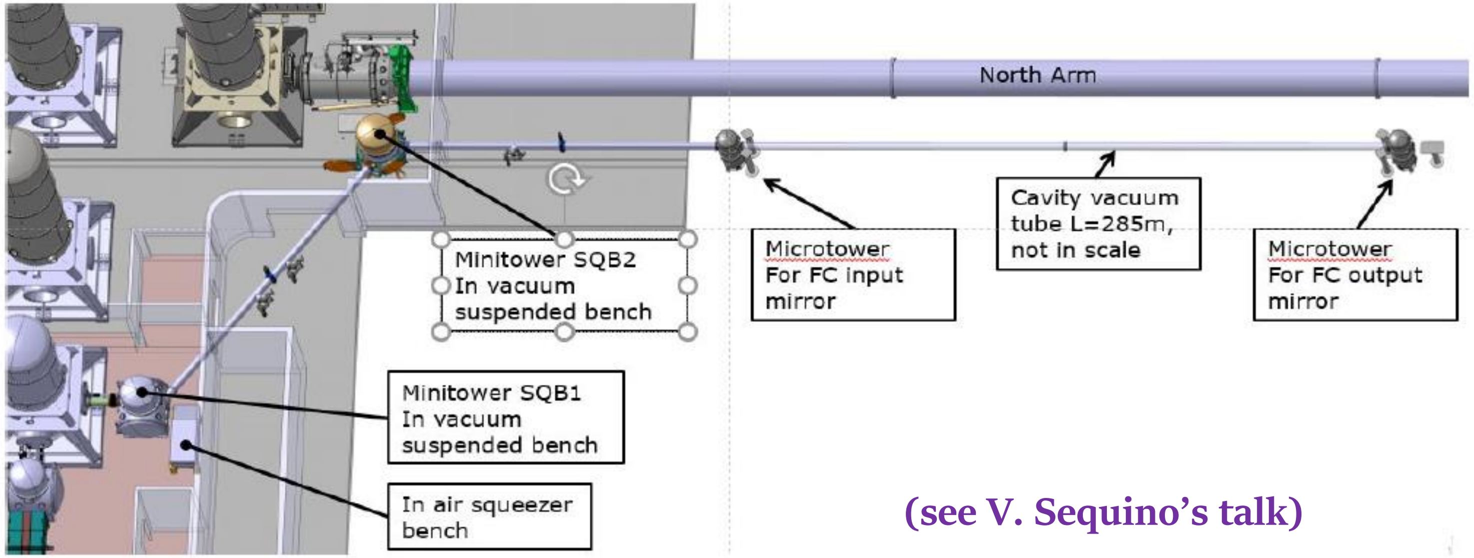
FC main properties

- Cavity length 285 m
- mirrors diameter 150 mm
- RoC of mirrors 558 m
- finesse 11000 (@1064 nm)
- finesse 100 (@532 nm)
- SQZ angle rotation @ 20-30 Hz
- round-trip losses < 40 ppm

Installation of optical in air and suspended in vacuum benches → to be completed in fall 2020



INFRASTRUCTURE WORKS for FC installation started in May 2020 → COMPLETED



(see V. Sequino's talk)

Main changes:

Larger beams on **End Test Masses**

- **6 cm radius → 10 cm radius**

Larger mass of End mirrors

- **42 kg → 105 kg**

Better mirror coatings

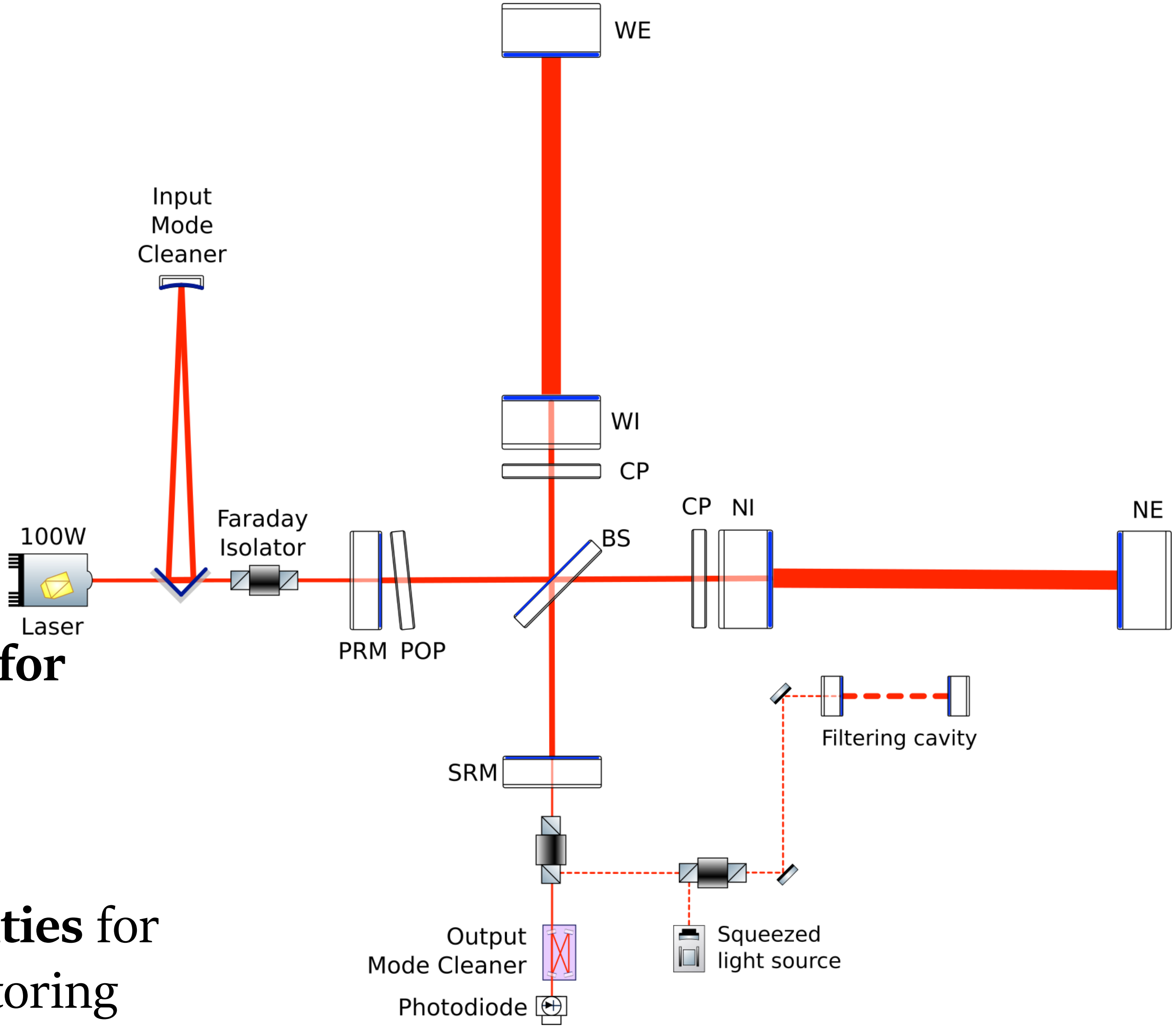
- Lower mechanical losses,
- less point defects,
- better uniformity

New suspensions/seismic isolators for large mirrors

Further increase of **laser power**

- **40 W → 60 W → 80 W**

Instrumented **baffles in the arm cavities** for **scattered light mitigation** and monitoring



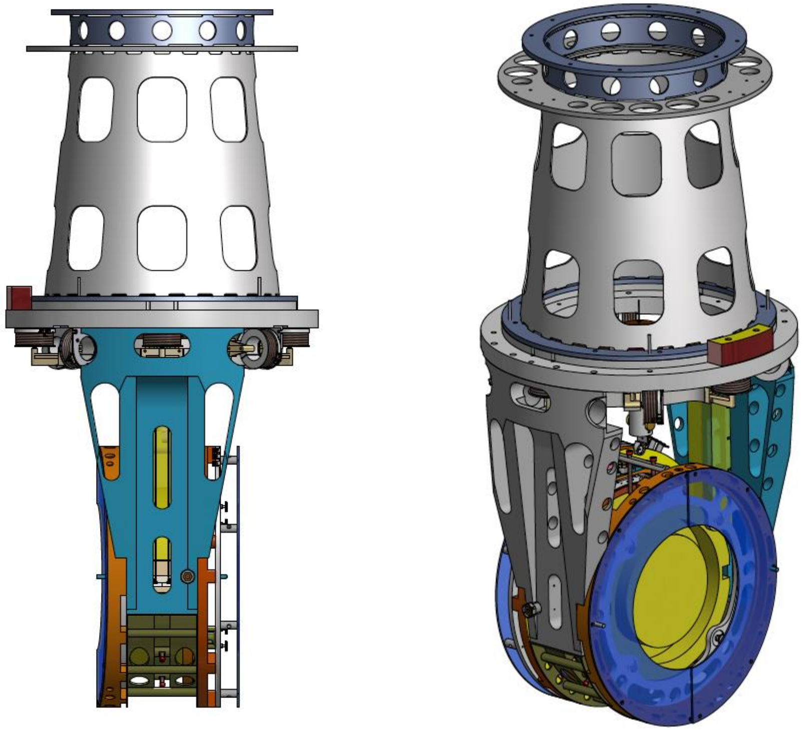
Advanced Virgo + Phase II: Large Mass Payloads (End Mirrors)

Larger mass end mirrors: 42 kg → 105 kg

Better mirror coatings: Lower mechanical losses, less point defects, better uniformity

New suspensions/seismic isolators for large mirrors

- First payload prototype design → done
- Dummy components for tests →designed/ordered/delivered
- Large Mass handling tools → under design
- Next:
  - Finalization of Anchor-Fiber-Anchor prototype design and assembly
  - Upgrade of SA blades design to be compliant with higher load (200 kg)
  - Start first tests in clean room



CAD by M. Perciballi

Prototype design advanced, actuation cage connection to SA developed by SAT is shown

Large mass implementation relevant not only to reduce coating thermal noise (CTN) but also in view of 3G detectors

Outline

- Advanced Virgo design
- First direct detection of Gravitational Waves
- Advanced Virgo in the last observing run O3
- Current upgrade before next observing runs O4,O5: Advanced Virgo+
- Conclusions and perspectives

Conclusions and Perspectives

- **First direct observation of GWs in O1: GW150914 → Birth of GW Astronomy**
- **AdV instr. upgrade**: heavier TM, new payloads, higher laser power, higher quality optics/coatings, TCS
- **Virgo joined O2 in August 2017**: 1 month 3 events **(GW170817 BNS → birth Multimessenger Astronomy)**
- O1-O2 catalogue: 11 GW events detected (10 BBHs, 1 BNS)
- **Before O3 AdV instr. upgrade**: **monolithic susp., Freq. Ind. Squeezing** → sensitivity improvement!
- **O3 catalogue**: 56 detection candidates, 3 confirmed and results published (**GW190521 first IMBH**)
- **Present: before run O4 AdV+ Phase I instr. upgrade: SR mirror, Freq. Dep. Squeezing**
- **Close future: O4 foreseen to start on Jan 2022**
- **Next future: before run O5 AdV+ Phase II instr. Upgrade: Large mass ETM (42 kg → 105 kg)**

Thank You
for
Your attention

Sibilla Di Pace, sibilla.dipace@roma1.infn.it

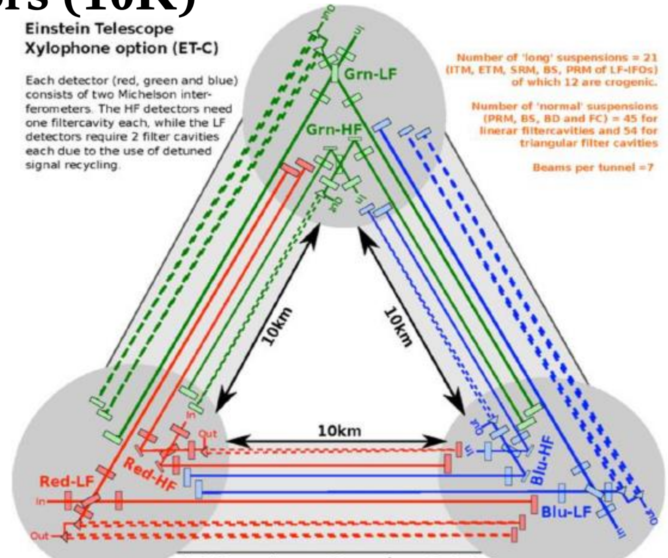
9th International Conference on New Frontiers in Physics 2020 Kolombary, Crete Greece

Extra Slides

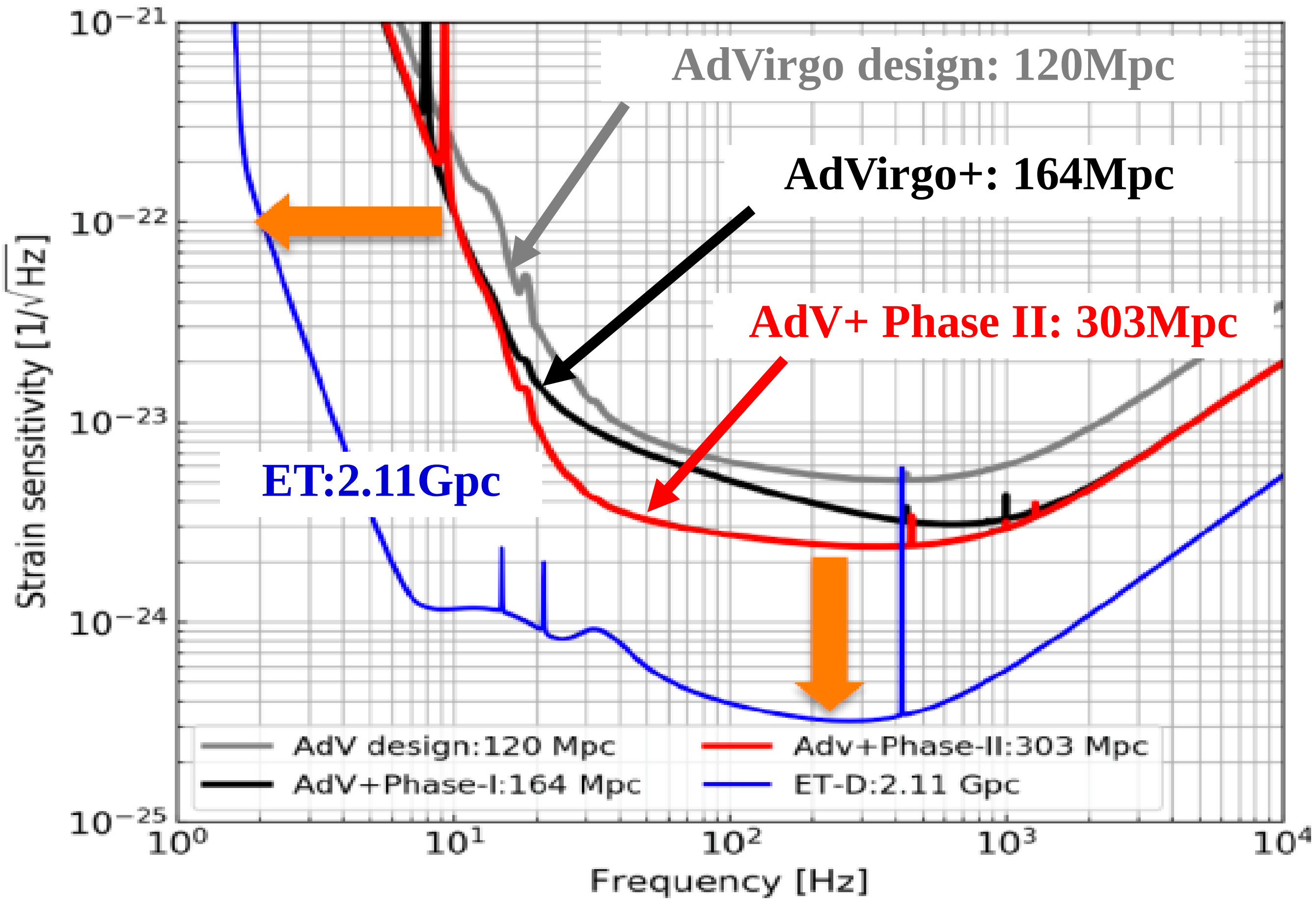
Third generation of GW detectors: Einstein Telescope (ET)

Our target: 10⁵ to 10⁶ events/year

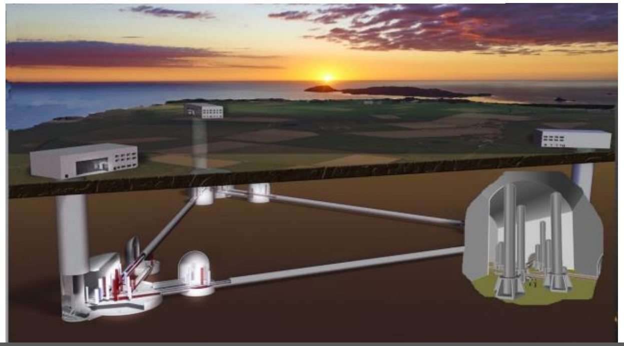
- Xylophone configuration = 3 detectors
- Arm cavities 10km long
- Underground (300m)
- Cooled mirrors (10K)



ET Design Study, 2011

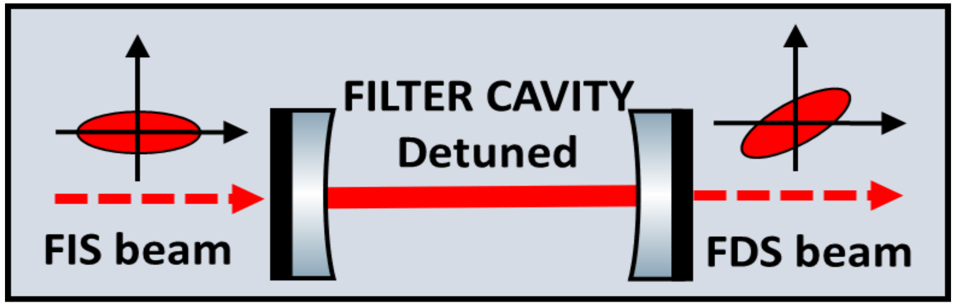


Merging BH throughout the whole universe and reconstruct BH demography
Explore new physics in gravity and fundamental properties of compact objects
Investigate connection between high energy process in radiation/particle VS gravitation
Investigate primeval universe and connections with particle physics



Filter Cavity (FC) for FDS angle rotation

A detuned Fabry-Pérot cavity can rotate the squeezing angle in a frequency-dependent way



Rotation induced by a FP cavity at a frequency Ω

$$\theta_{fc}(\Omega) = \arctan\left(\frac{2\gamma_{fc}\Delta\omega_{fc}}{\gamma_{fc}^2 - \Delta\omega_{fc}^2 + \Omega^2}\right)$$

FP cavity has a frequency dependent response:

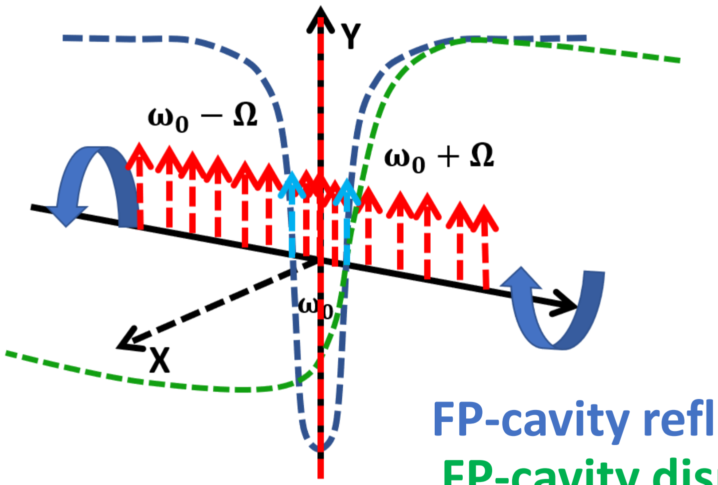
Important cavity parameters:

- linewidth γ_{fc}
- detuning $\Delta\omega_{fc}$

$$\Delta w_{fc} = \gamma_{fc} = \frac{\Omega_{SQL}}{\sqrt{2}}$$

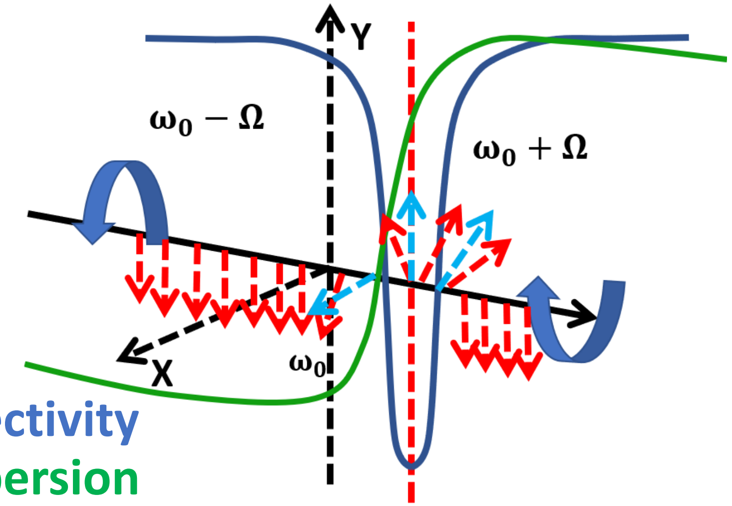
TUNED CONFIGURATION

Quantum noise sidebands don't experience the rotation



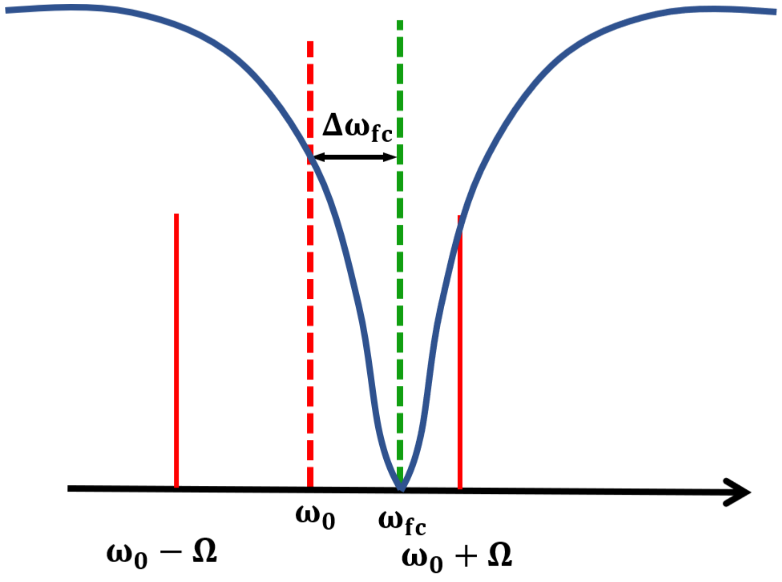
DE-TUNED CONFIGURATION

One quantum noise sideband experiences the rotation



FP-cavity reflectivity

FP-cavity dispersion



Birth of the Multimessenger Astronomy

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

The first time that a cosmic event has been viewed in both GWs and EM

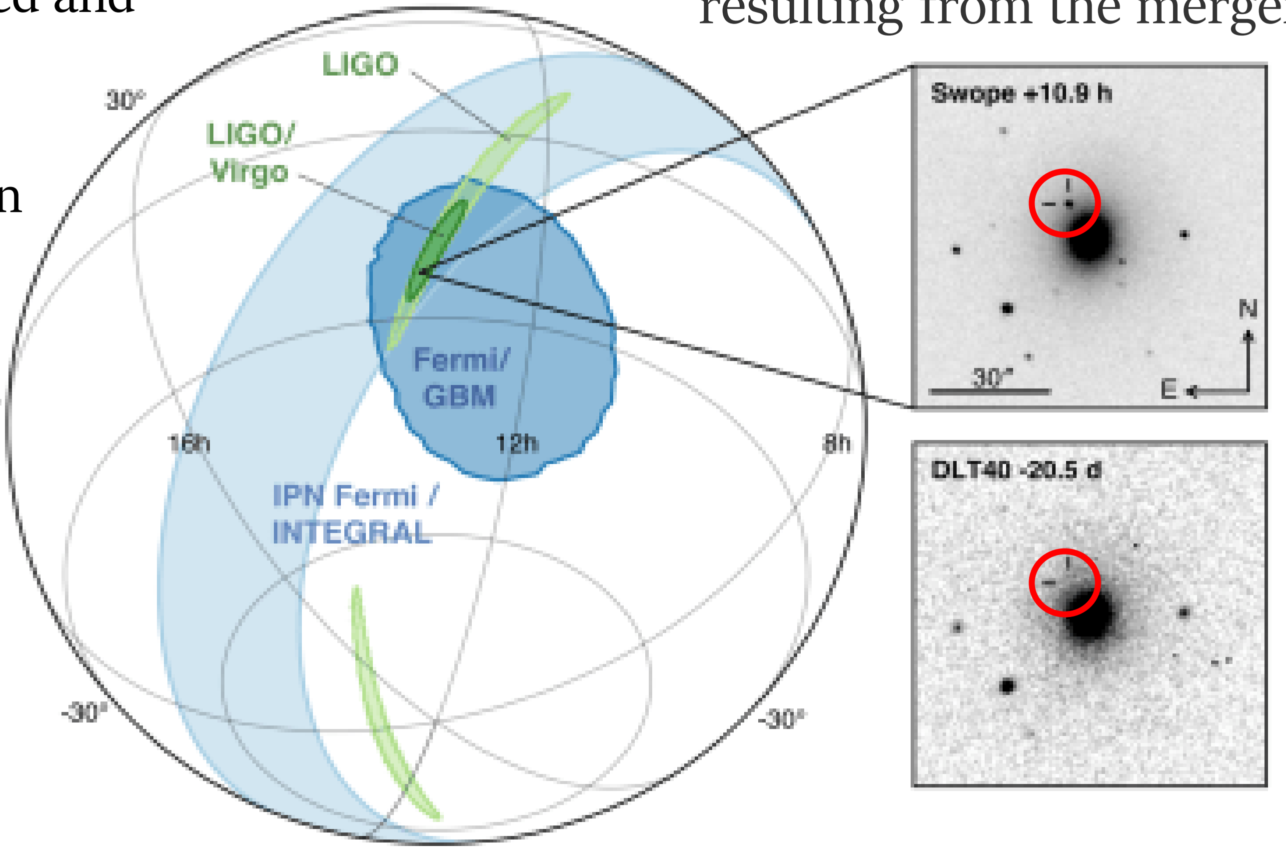
Electromagnetic counterpart observed by 70 ground based and space based observatories

Fundamental the contribution of Virgo to better localise the GW source

Source of GW170817

$$M_1 = 1.46\, M_{Sun}$$
$$M_2 = 1.27\, M_{Sun}$$
$$M_{end} \leq 2.8\, M_{Sun}$$
$$E_{GW} \geq 0.04\, M_{Sun}c^2$$
$$D_L = 40\ Mpc$$
$$= 1.2\ 10^{21} km$$

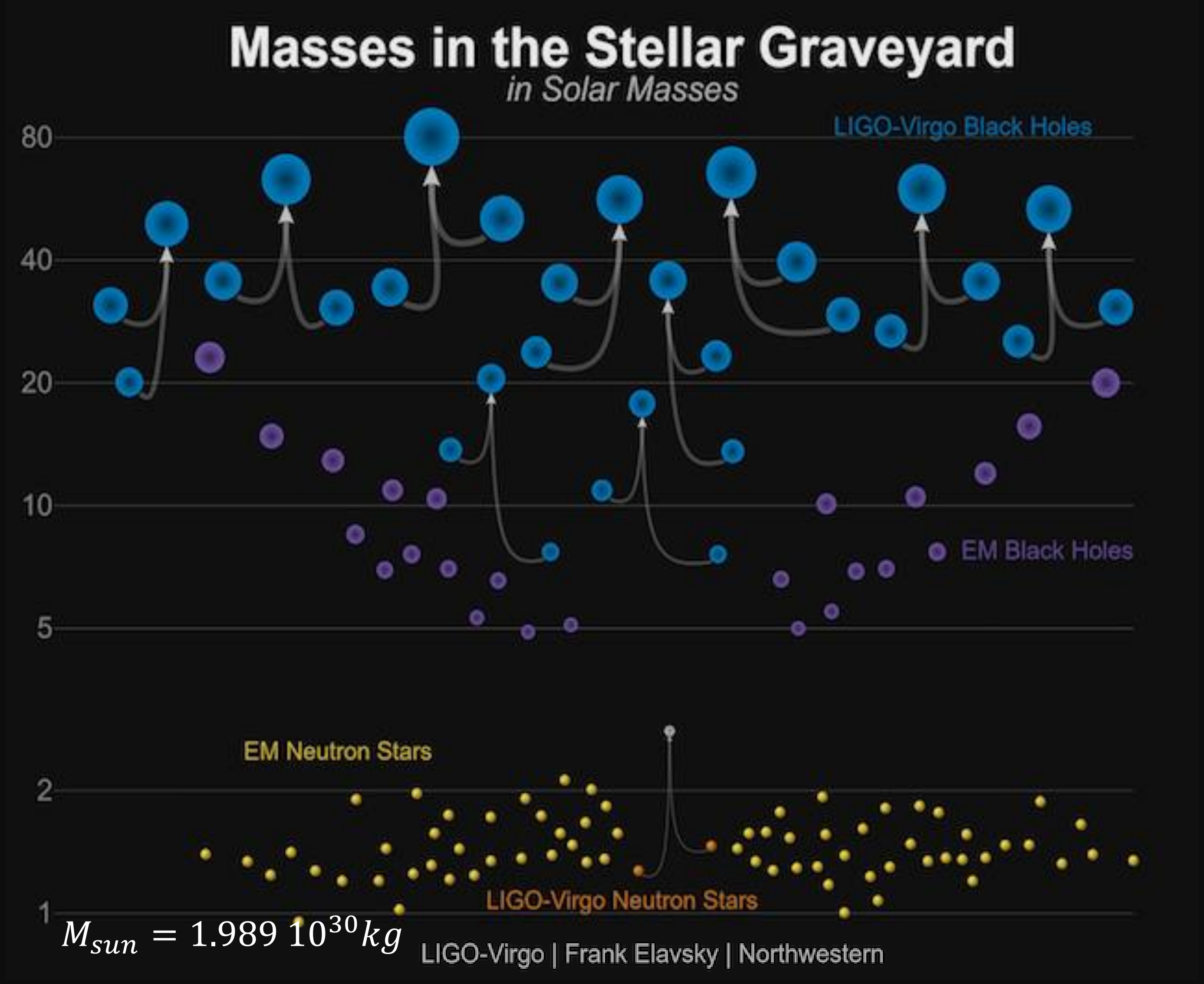
The first image of an 'optical transient' resulting from the merger of two NS



11hrs after GW signal Swope Satellite saw a short-lived visible fireball that appeared in the known galaxy **NGC4993**

Phys. Rev. Lett. **119**, 161101 (2017)

Mass catalogue of BBH & BNS in O1-O2



$M_{sun} = 1.989\ 10^{30} kg$

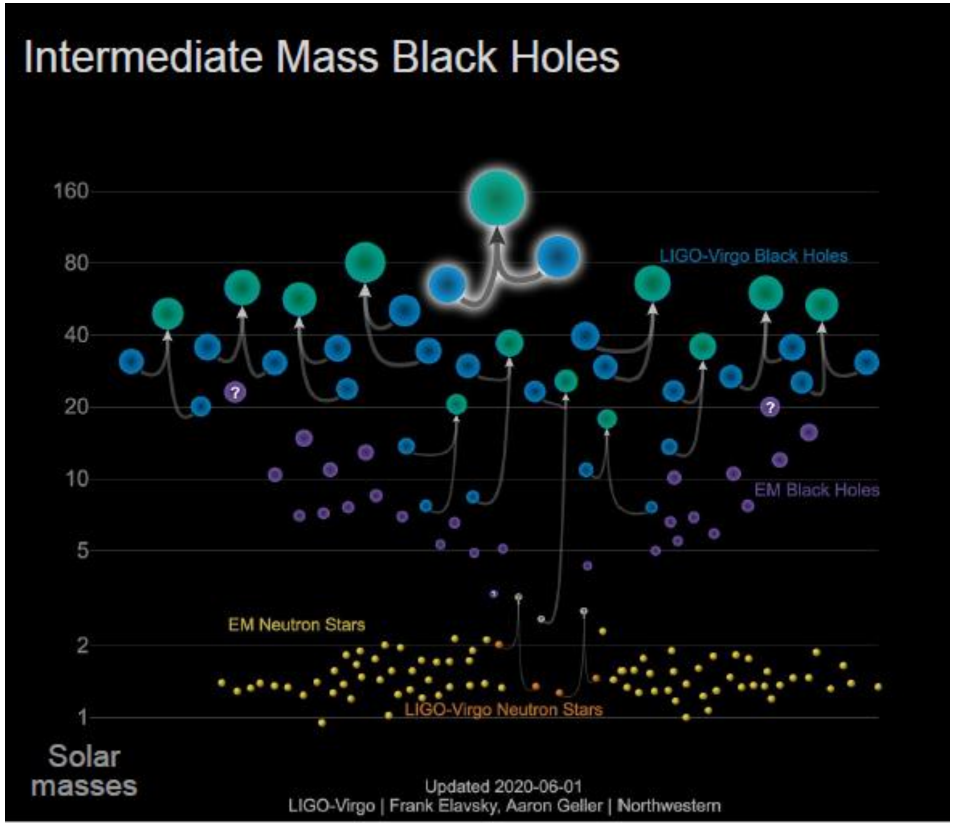
EVENT	$M_1(M_{Sun})$	$M_2(M_{Sun})$	$M_{end}(M_{Sun})$	$E_{GW}\ (M_{Sun}c^2)$
GW150914	35.6	30.6	63.1	3.1
GW151012	23.2	13.6	35.6	1.6
GW151226	13.7	7.7	20.5	1.0
GW170104	30.8	20.0	48.9	2.2
GW170608	11.0	7.6	17.8	0.9
GW170729	50.2	34.0	79.5	4.8
GW170809	35.0	23.8	56.3	2.7
GW170814	30.6	25.2	53.2	2.7
GW170817	1.46	1.27	≤ 2.8	≥ 0.04
GW170818	35.6	26.7	59.4	2.7
GW170823	39.5	29.0	65.4	3.3

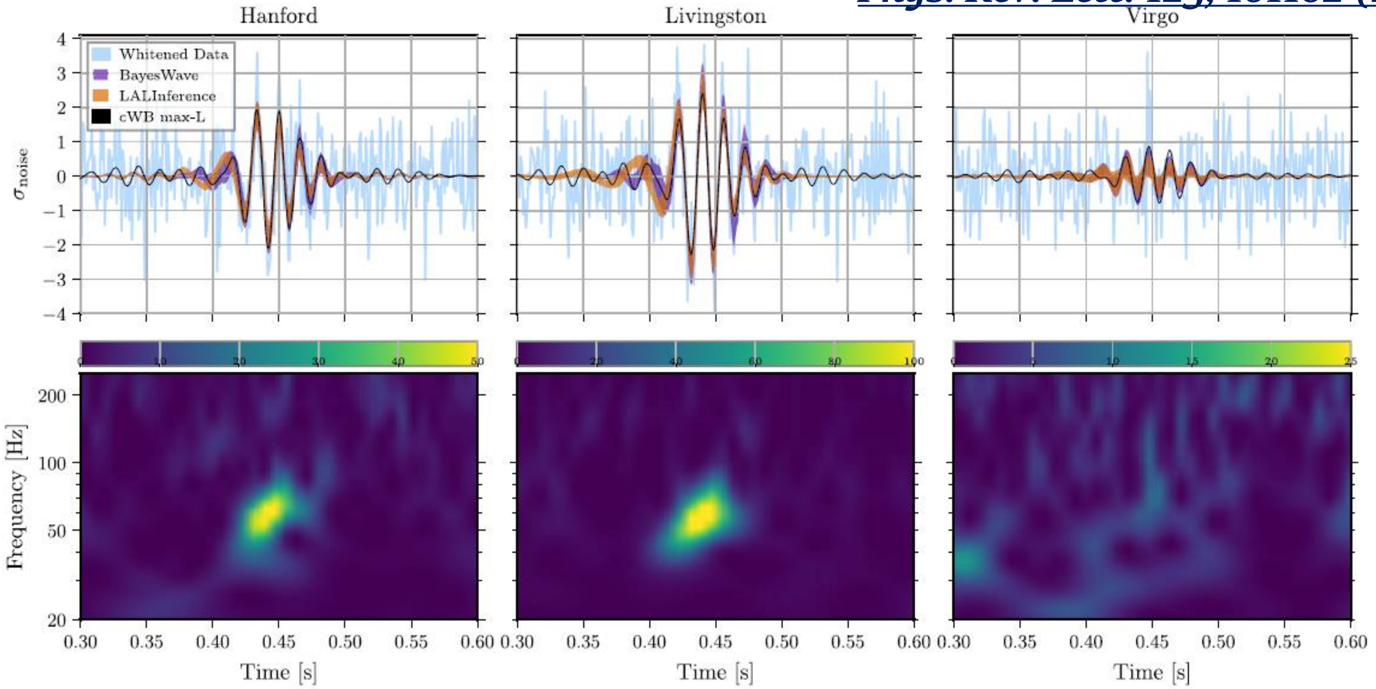
Still to be observed: SuperNovae, isolated Neutron Stars, stochastic background

GW190521: the most massive BH collision observed so far!

The resulting BH is the first of intermediate mass (IMBH) observed with GW

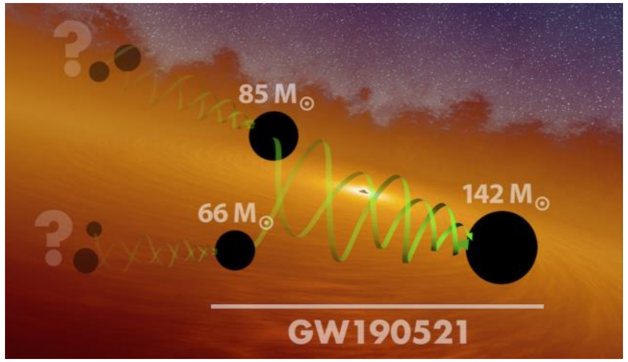
[Phys. Rev. Lett. 125, 101102 (2020)](#)





GW spectrograms: time-frequency representation of the GW signal from all 3 detectors

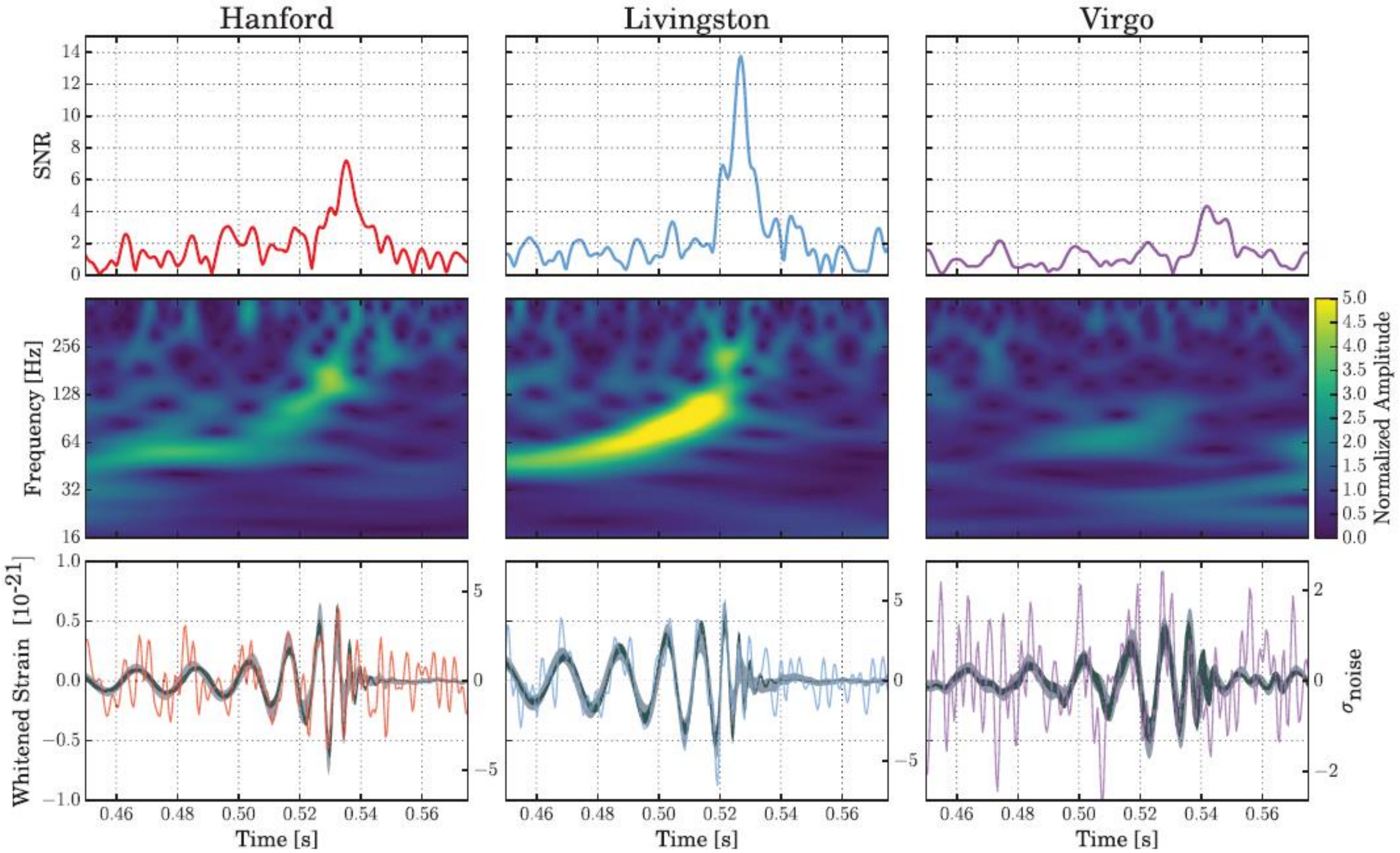
$$M_1 = 85\ M_{Sun}$$
$$M_2 = 66\ M_{Sun}$$
$$M_{end} = 142\ M_{Sun}$$
$$D_L = 5.3\ Mpc$$



The primary 2 BHs may have originated from former BBH collision

Several scenarios predict the formation of BHs in the so-called pair instability mass gap: they might result from the merger of smaller BHs or from the collision of massive stars or even from more exotic processes

A **network of 3 detectors** (2LIGOs and Virgo) **improves the sky localisation of the source**:
the area of the 90% credible region is reduced from **1160deg²** (2 LIGOs) to **60deg²** (2LIGOs and Virgo)



GW spectrograms: time-frequency representation of the GW signal from all 3 detectors

Source of GW170814

$$M_1 = 30.5\ M_{Sun}$$
$$M_2 = 25.3\ M_{Sun}$$
$$M_{end} = 53.2\ M_{Sun}$$
$$E_{GW} = 2.7\ M_{Sun}c^2$$

$$D_L = 540\ Mpc = 1.67\ 10^{22} km$$

$$SNR = 18$$

$$false\ alarm\ rate \ll \frac{1\text{event}}{27000\ \text{yrs}}$$

Advanced Virgo design: Thermal Compensation System

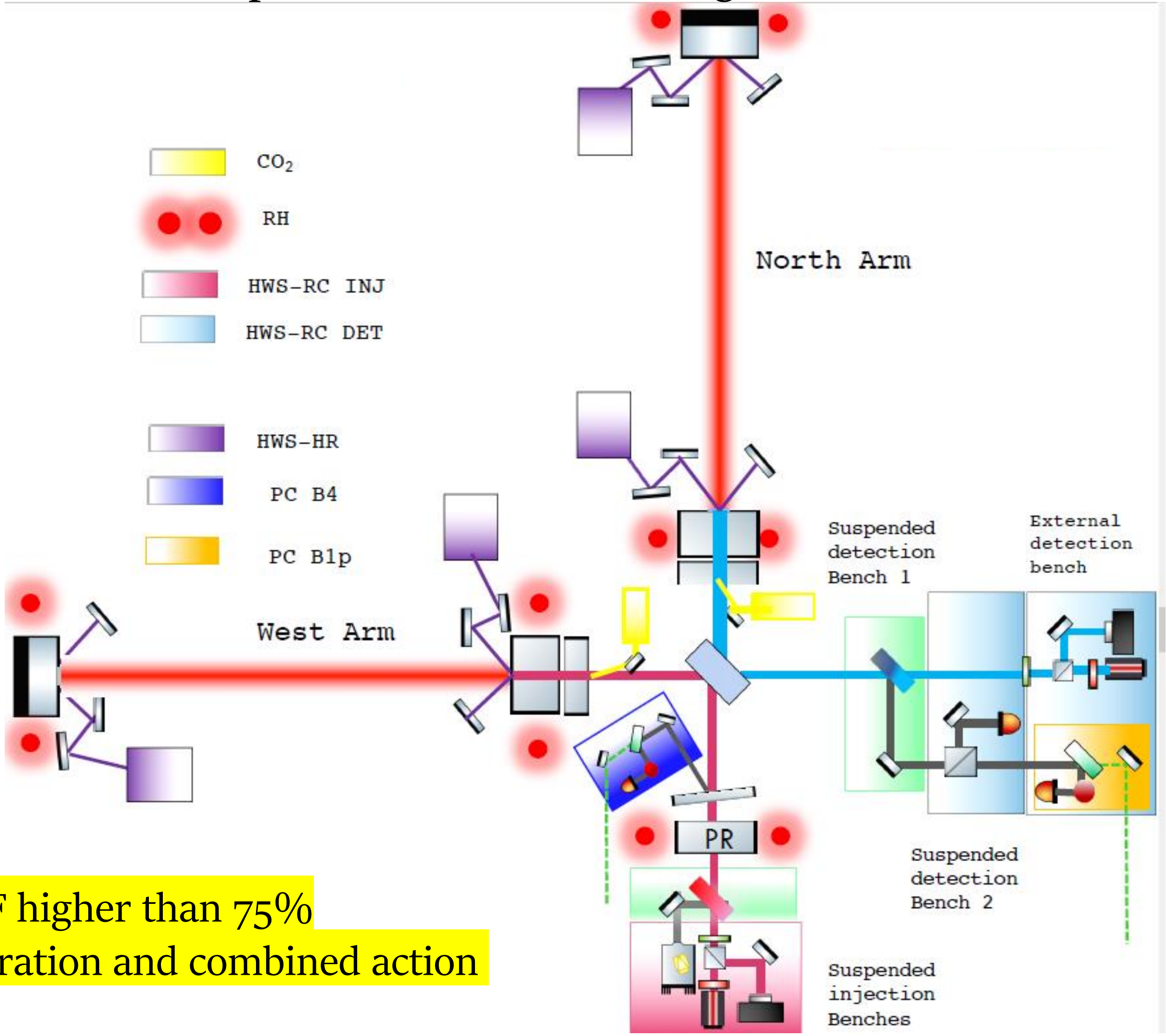
Thermal Compensation System (TCS) to compensate defects of core optics due to laser heating:

TCS actuators

- **Ring Heaters** (RH) act on the thermoelastic deformation of the HR surface
- **CO2 laser** projector corrects thermal lensing

TCS sensors

- **Hartmann Wavefront Sensors** in the recycling cavity (HWS-RC): used to measure the thermal lensing
- **Hartmann Wavefront Sensors** on the HR surface (HWS-HR): used to measure the thermoelastic deformation of the HR surface;
- **Phase cameras** (PC) used to sense independently the carrier and sidebands in the PRC and on the DP



- During O3 TCS was engaged ensuring a duty cycle of the ITF higher than 75%
- New R&D activities to optimize the TCS single actuators operation and combined action of multiple actuators for O4.