Virgo: past, present and future
Any lessons for ET?

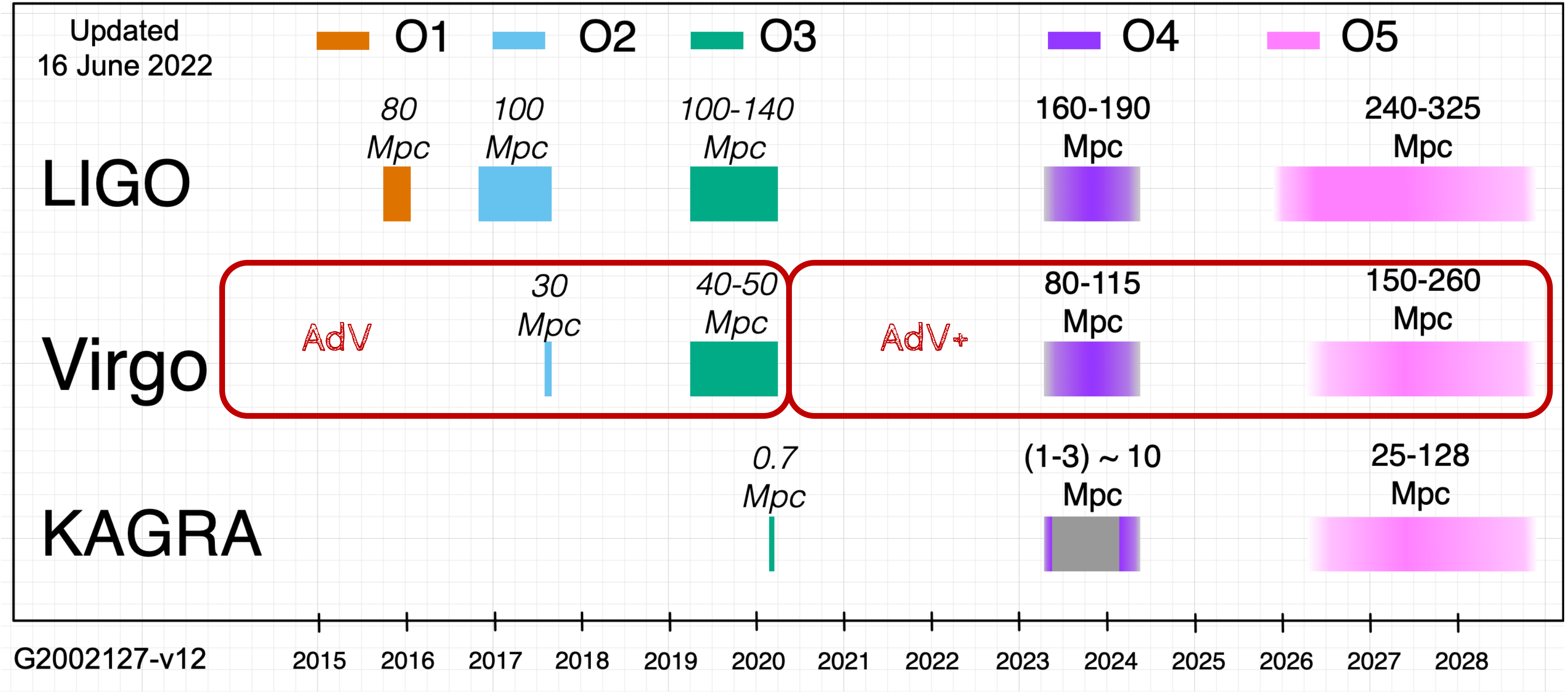
Giovanni Losurdo – INFN Pisa

VIR-1104A-22

Presenting work by the
Virgo Collaboration

VIRGO:
STATUS and PERSPECTIVES

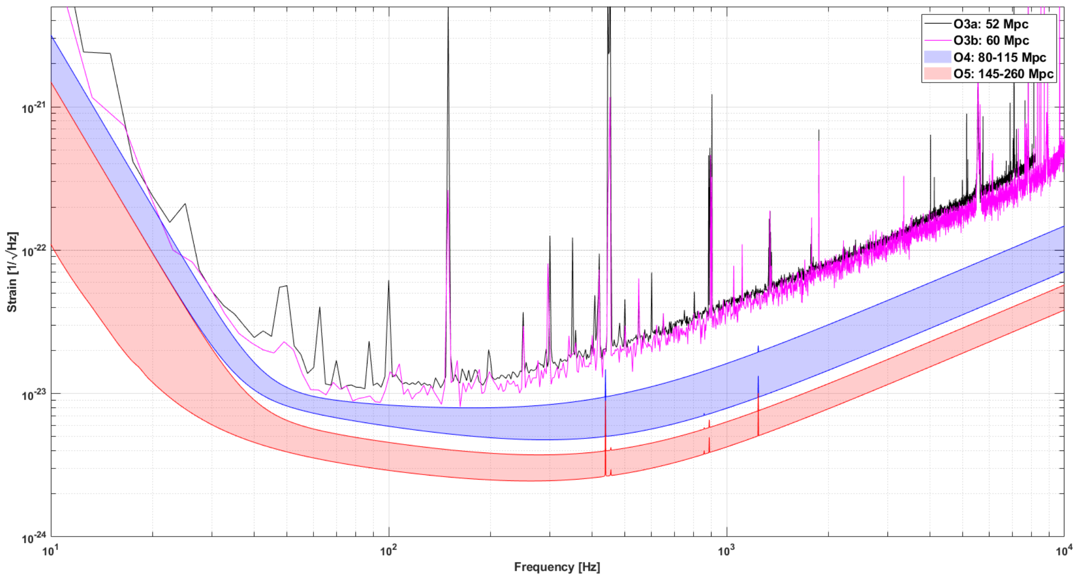
FRAMEWORK



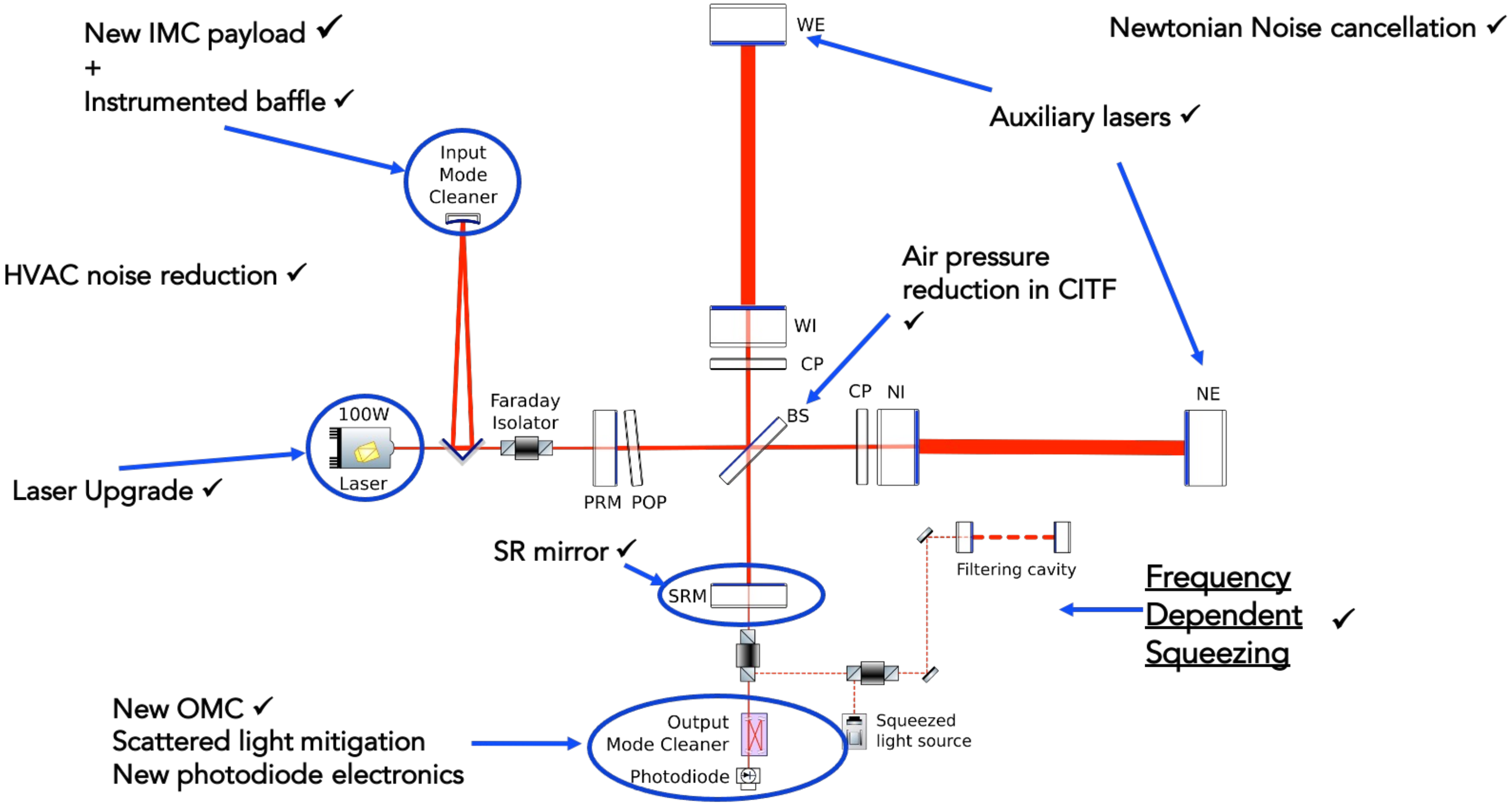
Updated
16 June 2022
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
160-190 Mpc
240-325 Mpc
Virgo
AdV
30 Mpc
40-50 Mpc
AdV+
80-115 Mpc
150-260 Mpc
KAGRA
0.7 Mpc
(1-3) ~ 10 Mpc
25-128 Mpc
G2002127-v12
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028

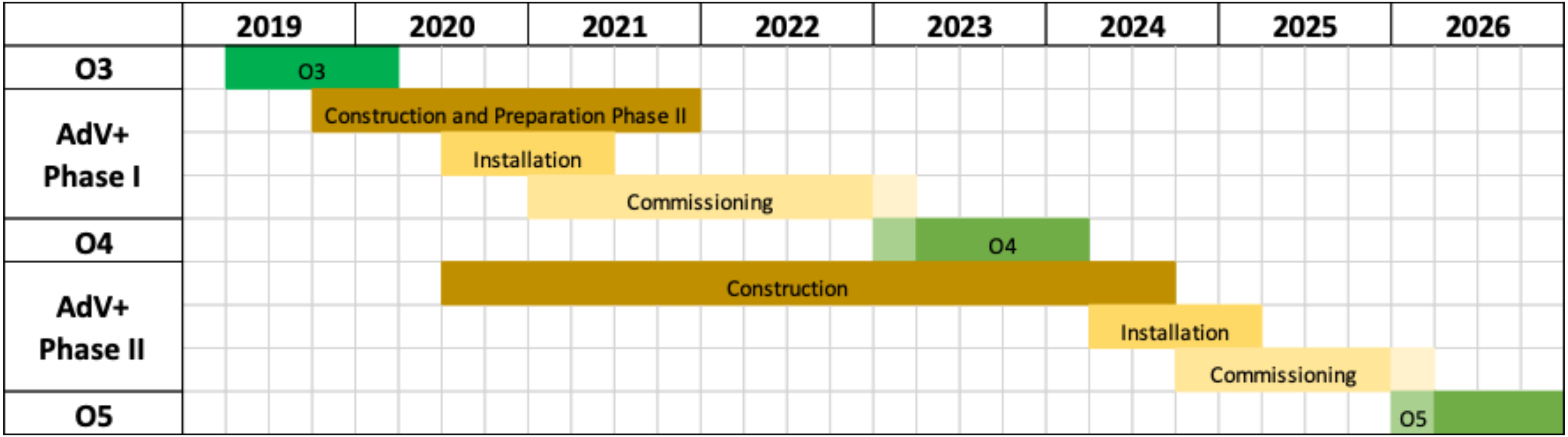
ADV+

- Virgo has a phased plan to increase its sensitivity: AdV+
  - Phase 1: reduce quantum noise, reach thermal noise limit
  - Phase 2: lower the thermal noise wall



AdV+/Phase 1

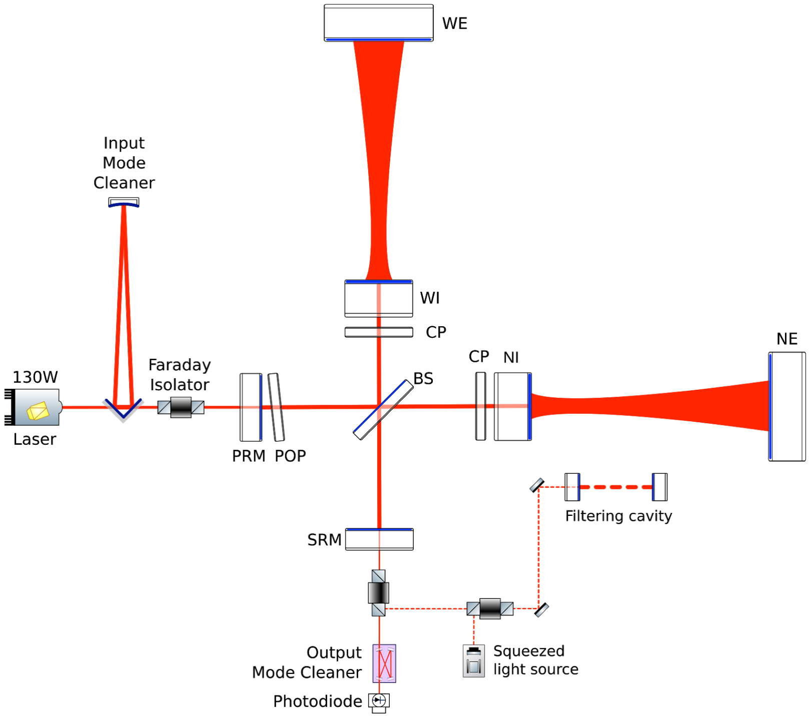

New IMC payload ✓
+
Instrumented baffle ✓
HVAC noise reduction ✓
Laser Upgrade ✓
Input Mode Cleaner
100W
Laser
Faraday Isolator
PRM
POP
WE
WI
CP
BS
CP
NI
NE
Newtonian Noise cancellation ✓
Auxiliary lasers ✓
Air pressure reduction in CITF ✓
SR mirror ✓
SRM
Filtering cavity
Frequency Dependent Squeezing ✓
Squeezed light source
Output Mode Cleaner
Photodiode
New OMC ✓
Scattered light mitigation
New photodiode electronics


2019
2020
2021
2022
2023
2024
2025
2026
O3
O3
AdV+ Phase I
Construction and Preparation Phase II
Installation
Commissioning
O4
O4
AdV+ Phase II
Construction
Installation
Commissioning
O5
O5

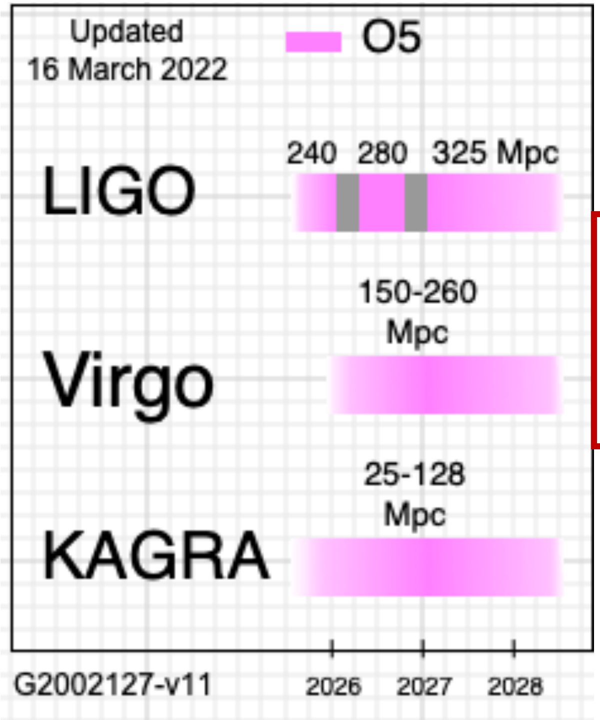
AdV+/II

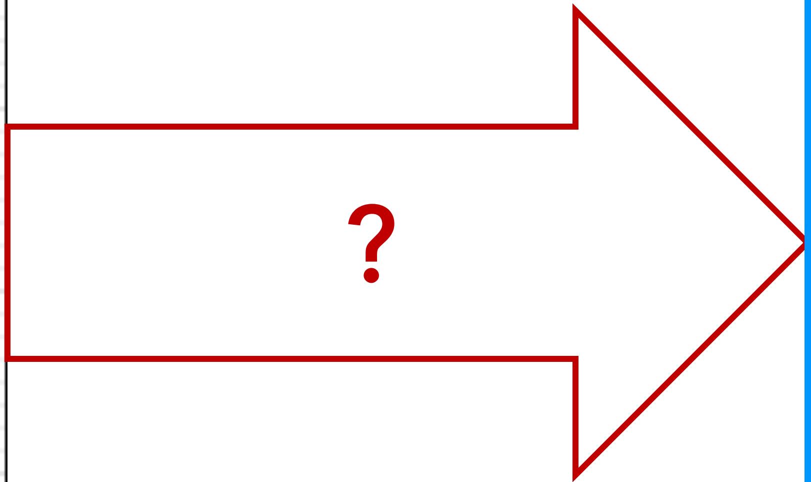
- Larger beams on end test masses
  - 6 cm radius ⇒ 10 cm radius
- Larger end mirrors
  - 35 cm diameter ⇒ 55 cm diameter
  - 40 kg ⇒ 100 kg
- Better mirror coatings
  - Lower mechanical losses, less point defects, better uniformity
- New suspensions/seismic isolators for large mirrors
- Further increase of laser power

  40W ⇒ 60W ⇒ 80 W



Post O5





3G

Is there the case for a new upgrade of the existing detectors?

Virgo_nEXT

- A concept study for a new, substantial Virgo upgrade aiming to exploit the infrastructure to its limits
    - Show that there is the science case for a new (sustainable) investment
    - Identify needed R&D lines and synergies with 3G
- Main goals: make great science, keep the GW community together bridging 2G+ and 3G, <u>reduce risks for ET</u>

- Document submitted to funding agencies
- Not yet a baseline design
- Maintains 1064 nm wavelength, room temperature

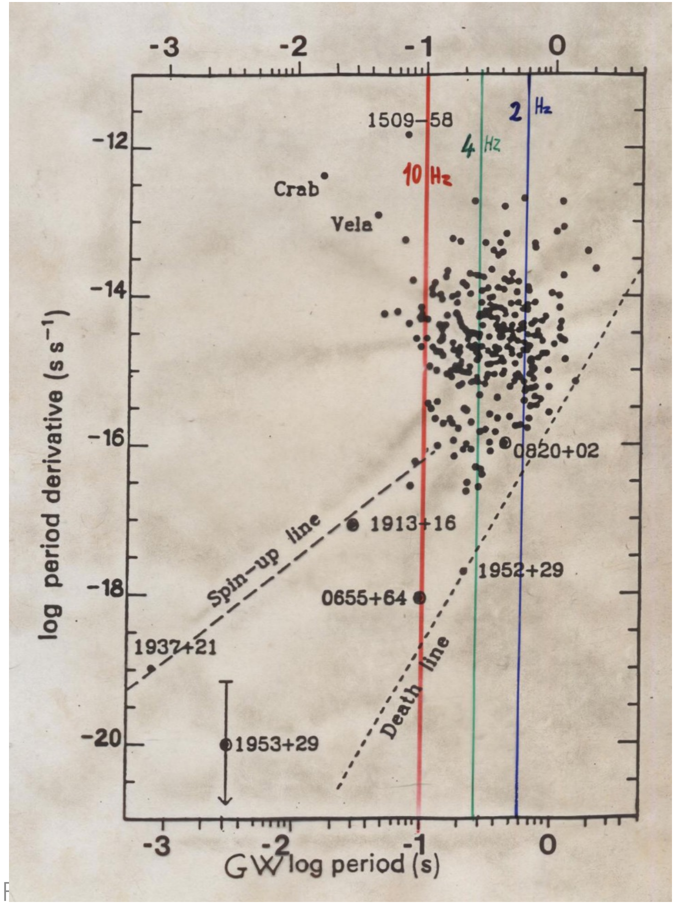
Parameter	O4 high	O4 low	O5 high	O5 low	post-O5low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 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

- Virgo_nEXT aims to developing technologies relevant for ET-HF
    - Similar circulating power and test mass weight (1.5 MW/105 kg vs 3 MW/200 kg)
    - Similar squeezing target (10 dB)
    - Coating
- Will continue to pursue the 10 Hz LF challenge, allowing to study/understand LF noises
- Overall, there is a strong **Virgo-ET synergy** in the case for Post-O5

VIRGO:
SOME LESSONS LEARNED

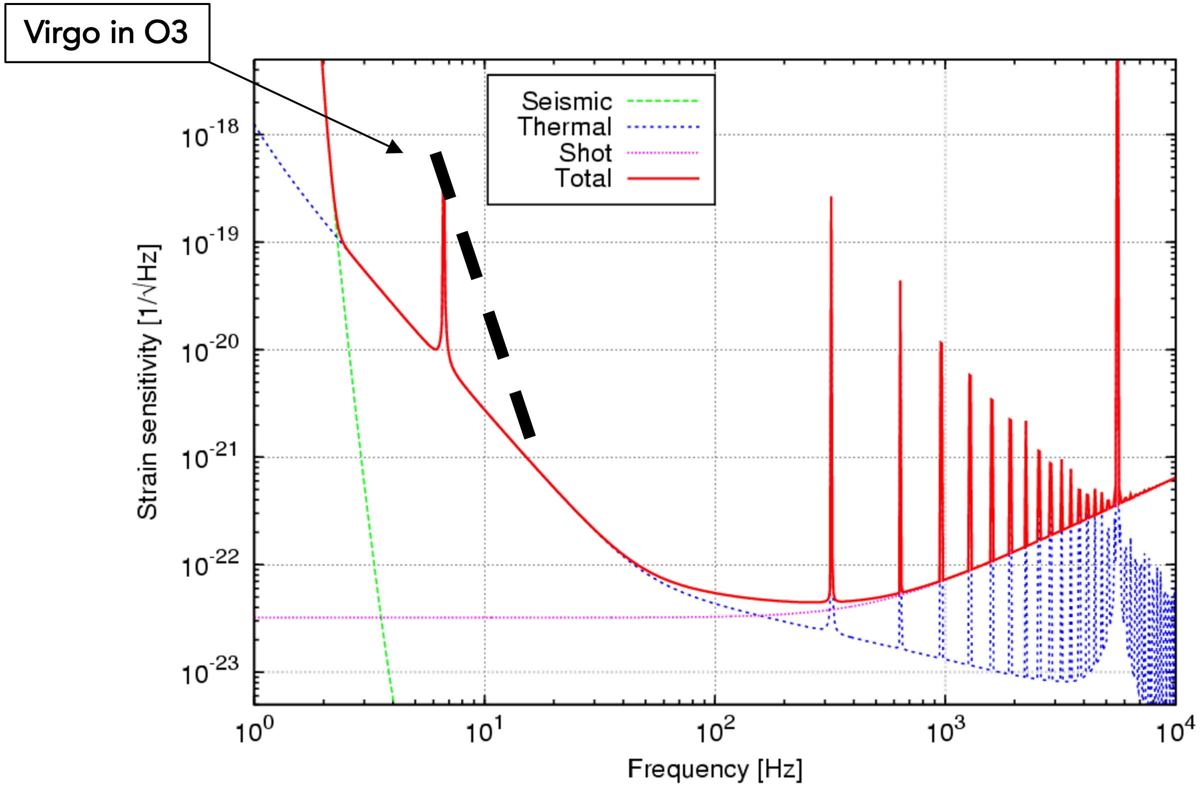
LOW FREQUENCY

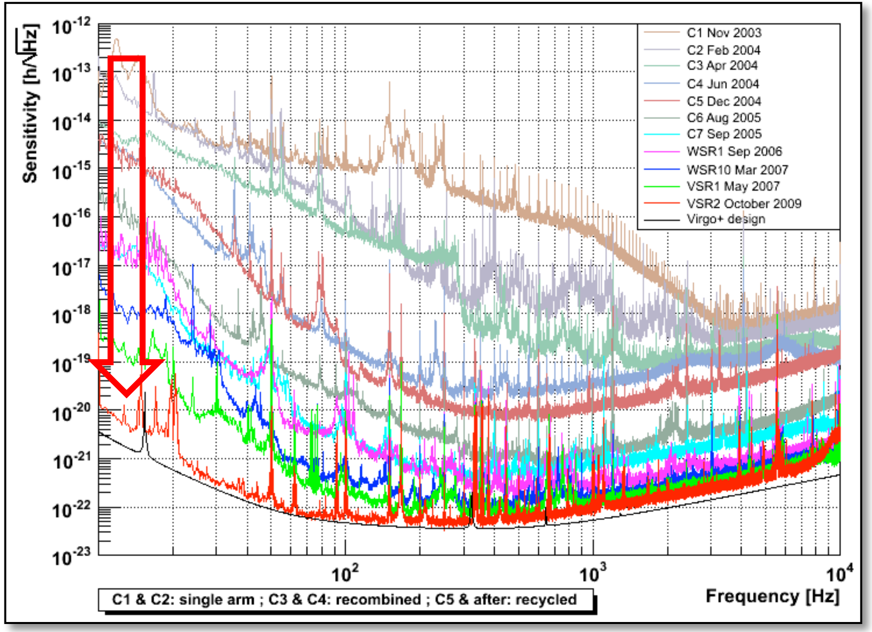
A Giazotto, 1980



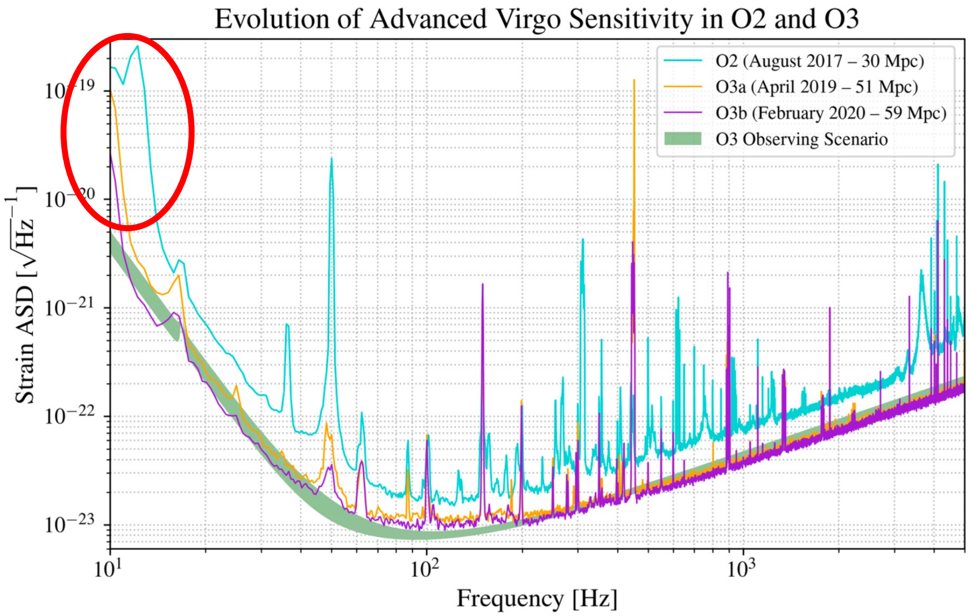
- Virgo was conceived a detector with low frequency threshold (10 Hz)
- Giazotto was thinking about detecting continuous sources (pulsars)
- The LF target became the main focus of the Virgo science case: "*LIGO is longer and has 2 detectors, but Virgo has the LF sensitivity*"

INITIAL VIRGO TARGET



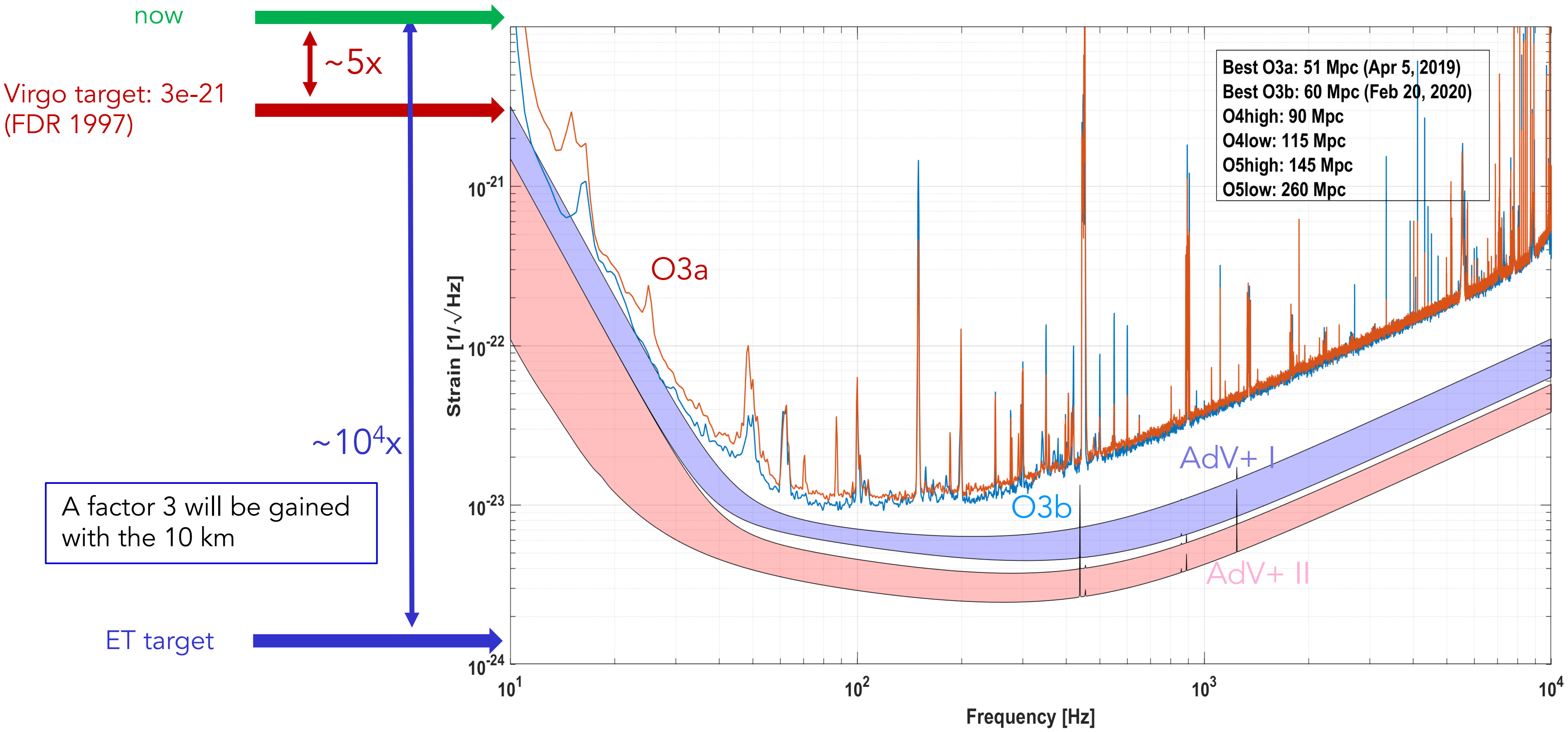


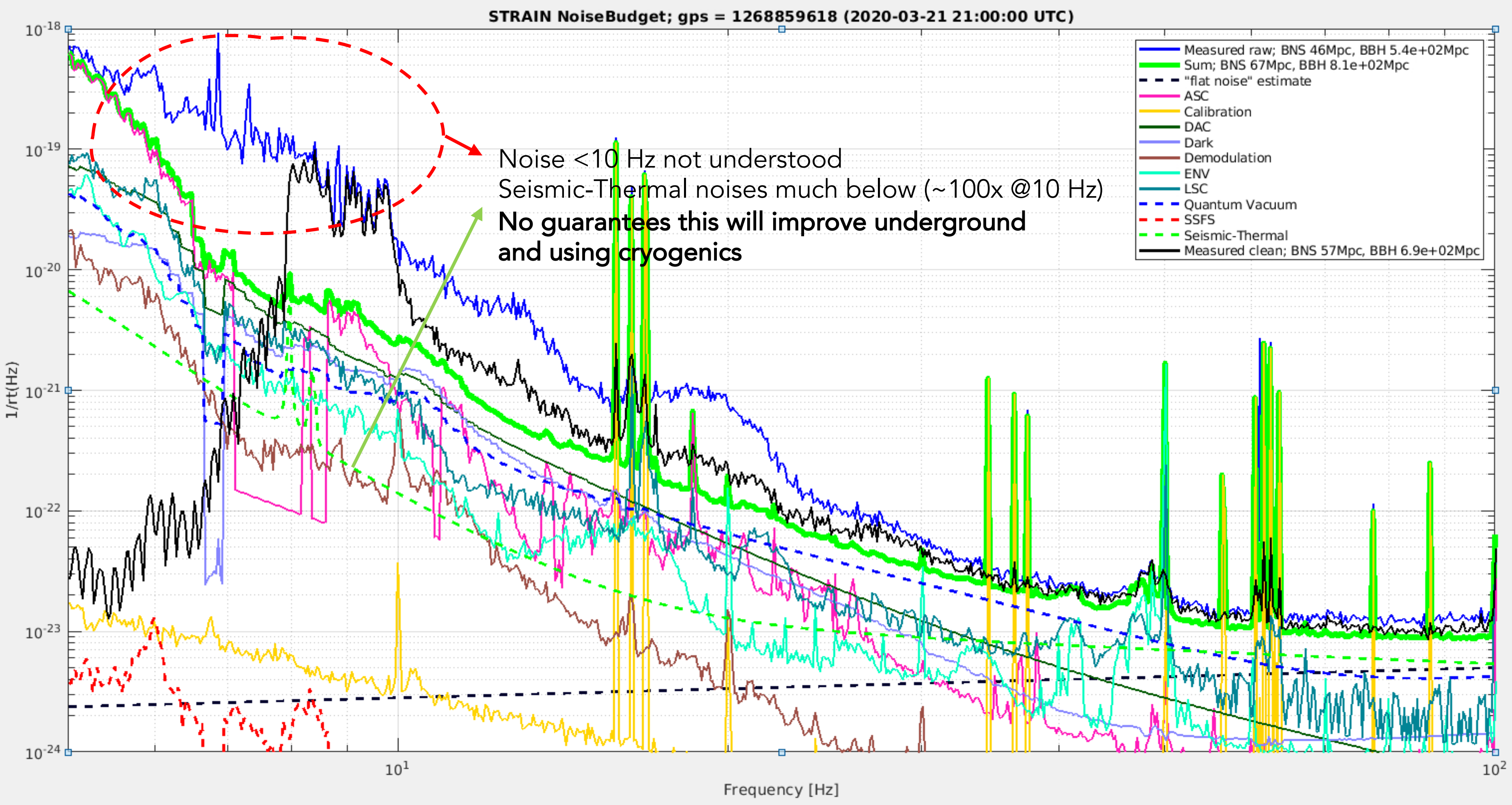
The LF sensitivity improved in the years of the initial Virgo commissioning…



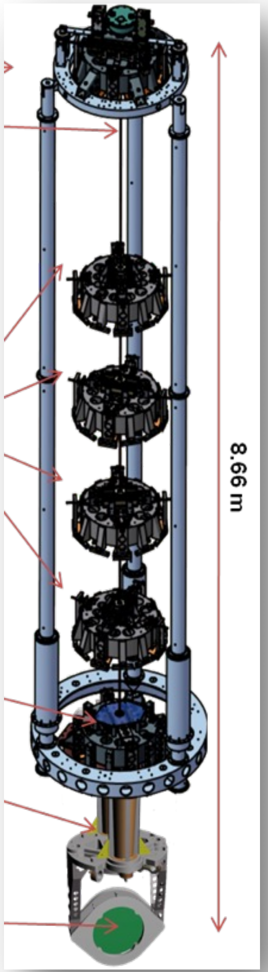
…then it was "stuck" at $h>10^{-20}$ @10 Hz **despite superattenuators** and **fused silica fibers**

STRAIN NOISE @10 Hz

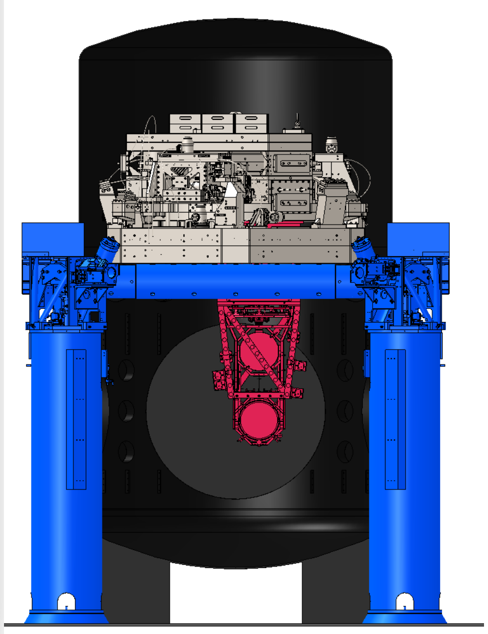


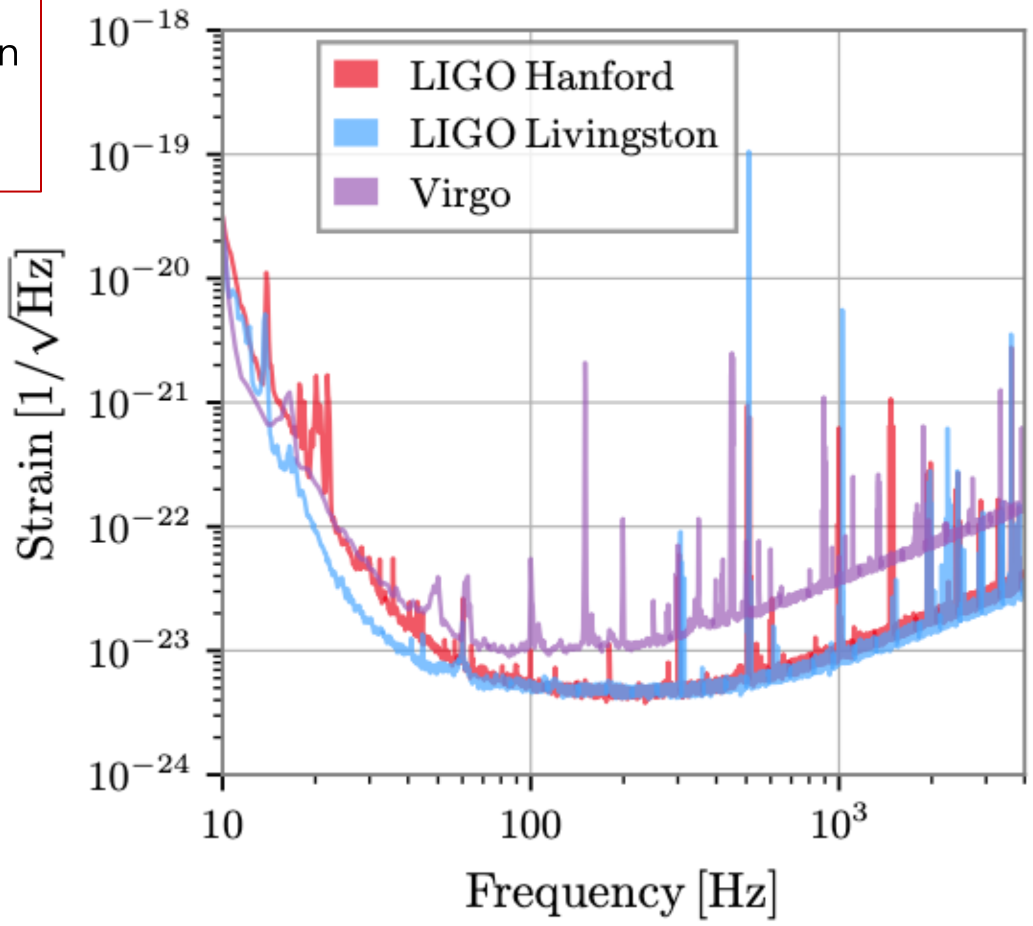


STRAIN NoiseBudget; gps = 1268859618 (2020-03-21 21:00:00 UTC)
Measured raw; BNS 46Mpc, BBH 5.4e+02Mpc
Sum; BNS 67Mpc, BBH 8.1e+02Mpc
"flat noise" estimate
ASC
Calibration
DAC
Dark
Demodulation
ENV
LSC
Quantum Vacuum
SSFS
Seismic-Thermal
Measured clean; BNS 57Mpc, BBH 6.9e+02Mpc
Noise <10 Hz not understood
Seismic-Thermal noises much below (~100x @10 Hz)
No guarantees this will improve underground
and using cryogenics
1/rt(Hz)
Frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}



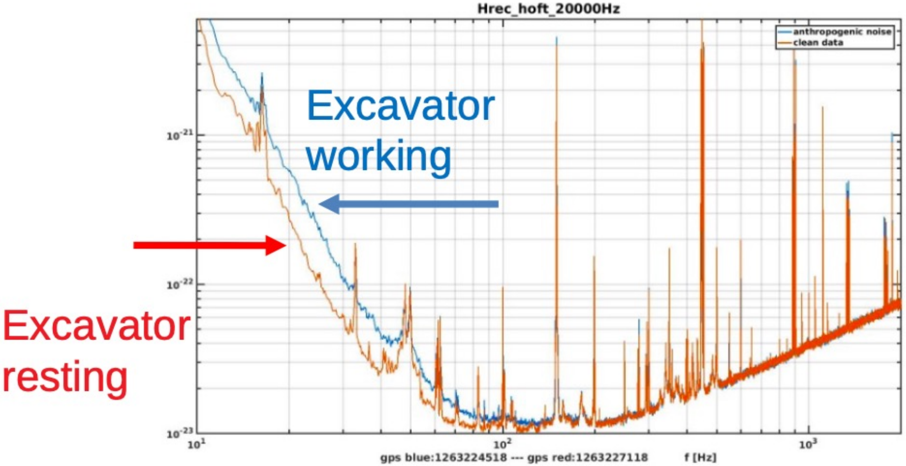
Advanced LIGO/Virgo:
different vibration isolation technologies,
comparable LF sensitivity





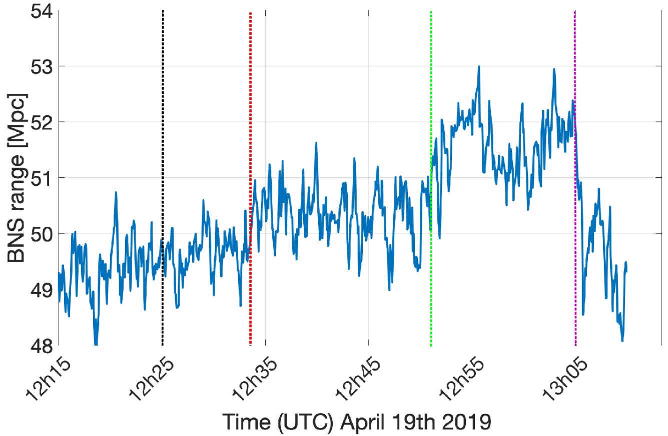
ANTROPOGENIC NOISE

Romero et al., VIR-0296A-20

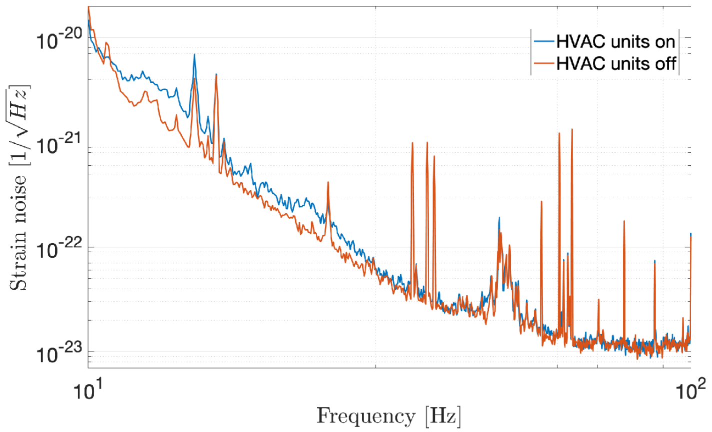


- Virgo experience: machine activity near the site makes interferometer low noise operation impossible

- Also, machines in the halls have a direct effect on LF sensitivity



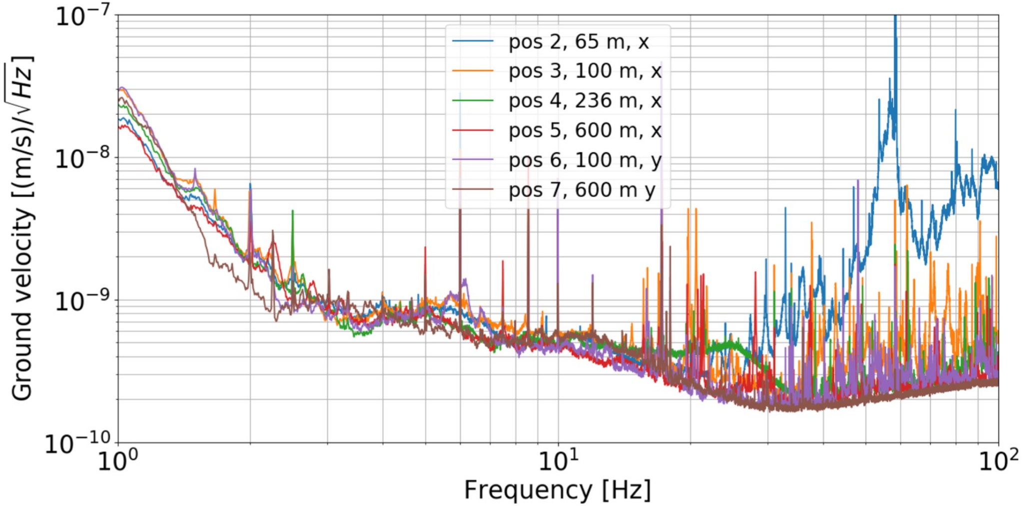
(**a**) Evolution of BNS range during the sequential HVAC switch off actions.



(**b**) AdV sensitivity before (blue) and while all heating, ventilation, and air conditioning (HVAC) units were off (red).

Fiori et al, Galaxies, 2020

FRANCESCA BADARACCO *et al.* PHYS. REV. D **104,** 042006 (2021)



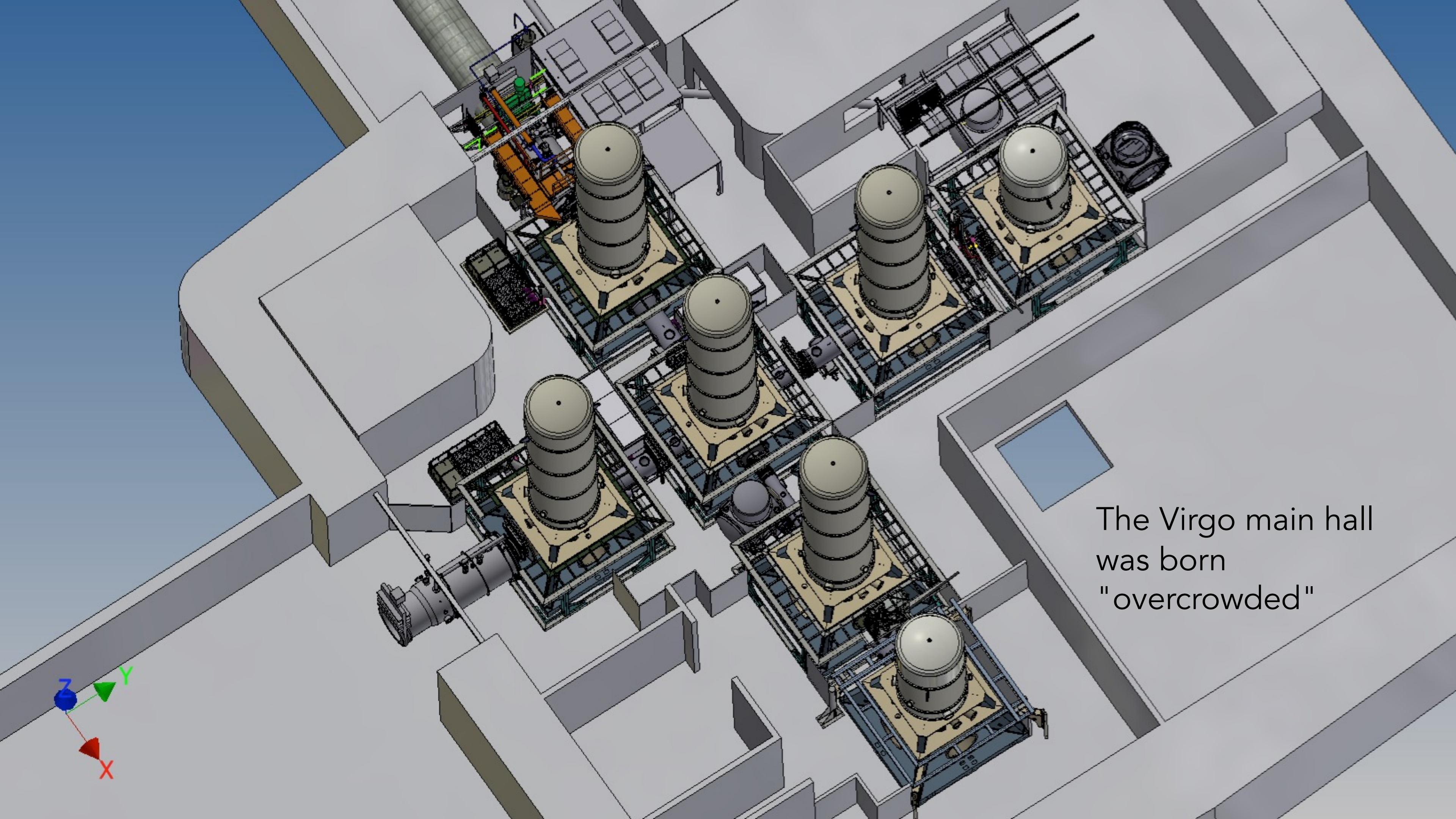
III. SEISMIC NOISE

In this section, we show the analysis results of the seismic data collected in the locations shown in Fig. 1. We need to make a remark. The excess noise that we can see in Fig. 3 at position 2, is greatly reduced during GW observations. Indeed, many noisy machinery are switched off during science mode; however, many others will need to run. Therefore, KAGRA plays an important role in the research and development studies for underground 3rd generation detectors (like ET); indeed, we know that machines such as ion vacuum pumps, cryocoolers, and air conditioners need to work even in science mode to provide the needed working conditions for the detector.

Seismic noise in Kagra cavern largely dominated by machine-induced vibrations above 20 Hz

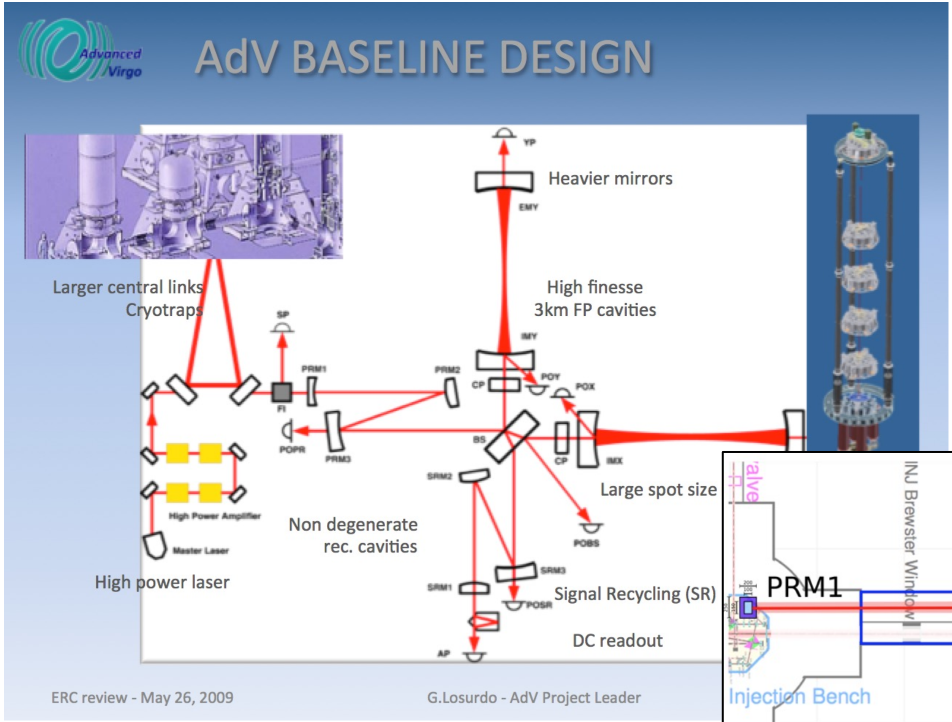
Running machines can partly spoil the gain of being underground

AdV – INFRASTRUCTURE ISSUES



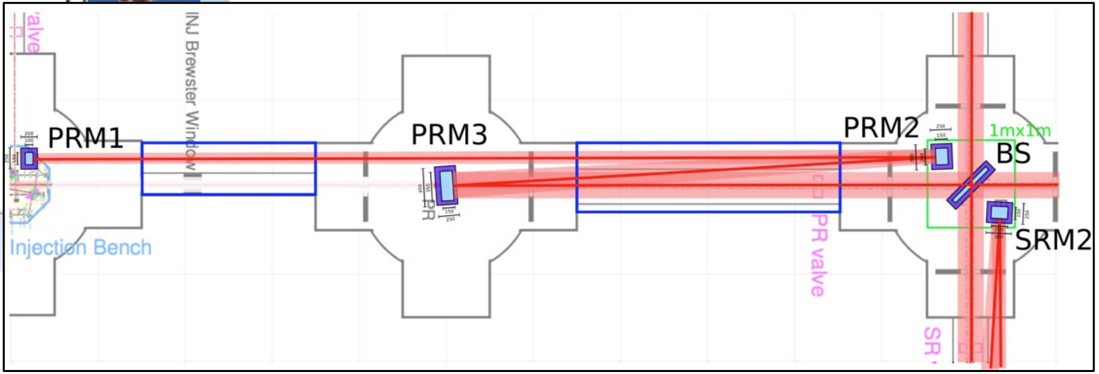
The Virgo main hall
was born
"overcrowded"

THE 2009 DESIGN WAS BASED ON STABLE RECYCLING CAVITIES
IT REQUIRED TO INVENT "MULTI-PAYLOADS": NO ROOM TO ADD MORE TOWERS



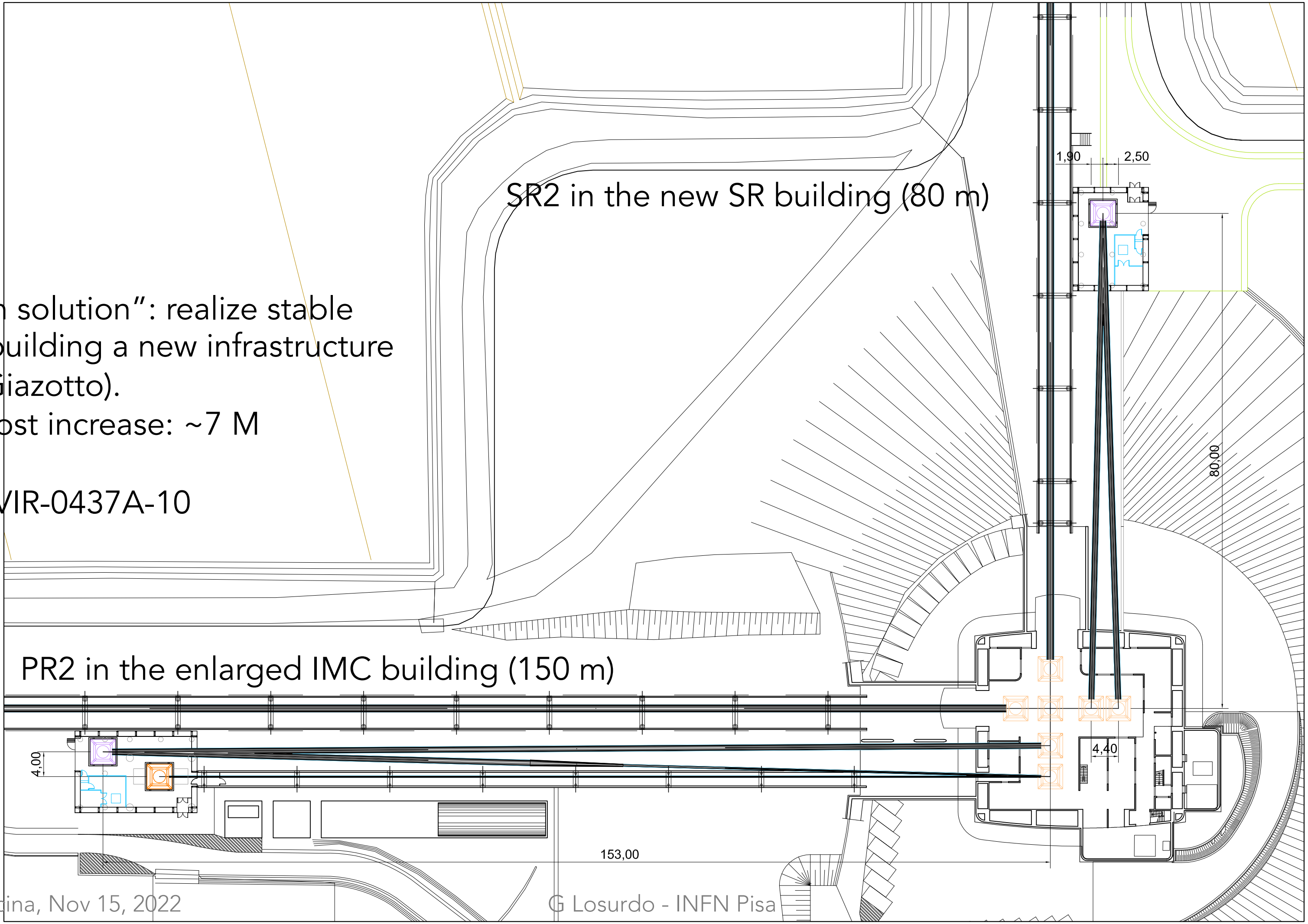
EVENTUALLY CONSIDERED TOO RISKY

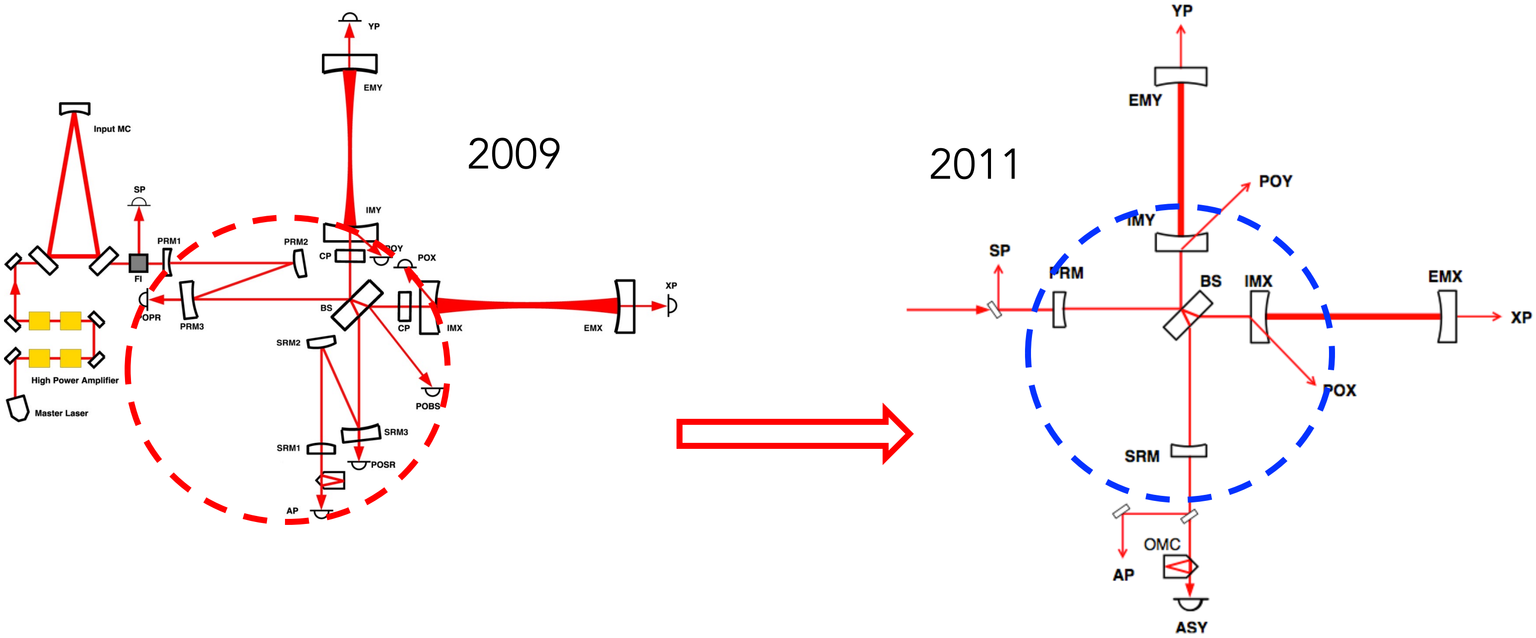
Freise et al, VIR-0025A-09 (2009)



The "golden solution": realize stable cavities by building a new infrastructure (idea by A Giazotto).
Estimated cost increase: ~7 M

VIR-0437A-10





- It was impossible to realize stable recycling cavities (baseline!)
  - Difficult to suspend >1 mirror from a SA
  - **No room** for more towers, **no budget** for new infrastructure/vacuum

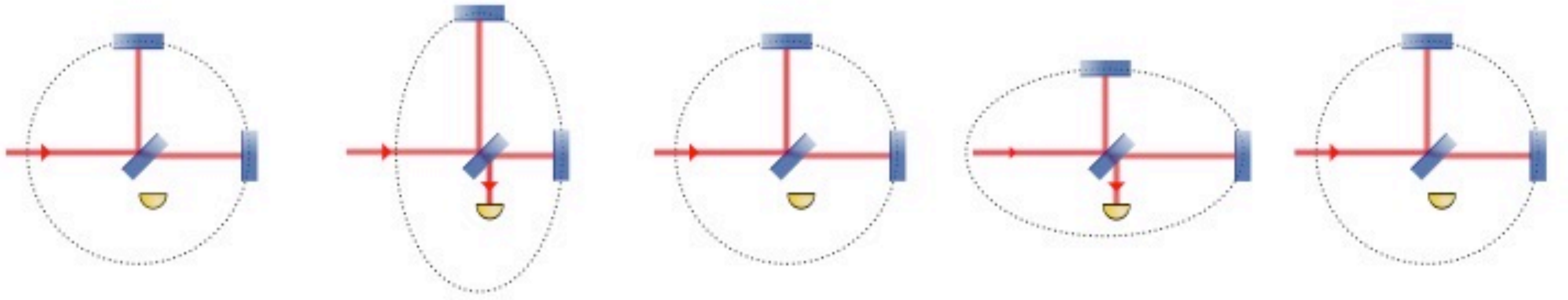
- AdV was re-designed with marginally stable recycling cavities

On the other hand, Virgo tunnels were designed large enough to allow for a smooth assembly…

…and the installation of crucial upgrades

SCHEDULE, LENGTH, NETWORK

INCREASING THE SENSITIVITY



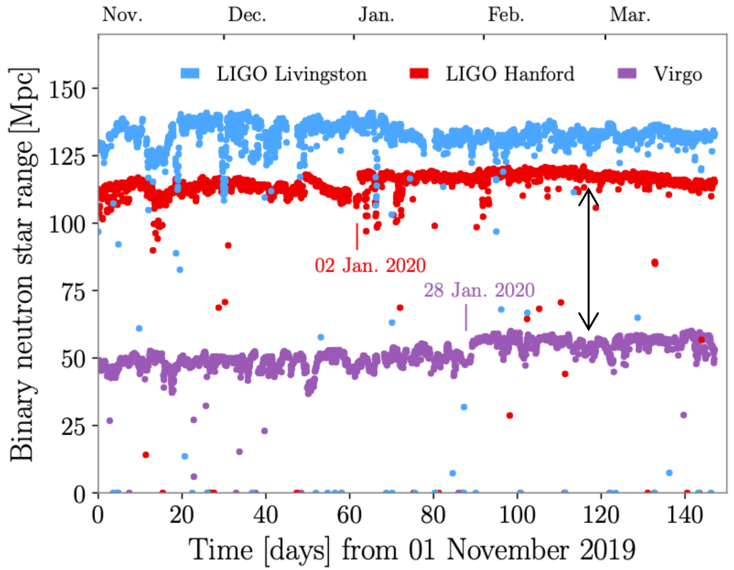
REDUCE NOISE
(technology, R&D)
€
⏱⏱⏱ (time = money)
High risk

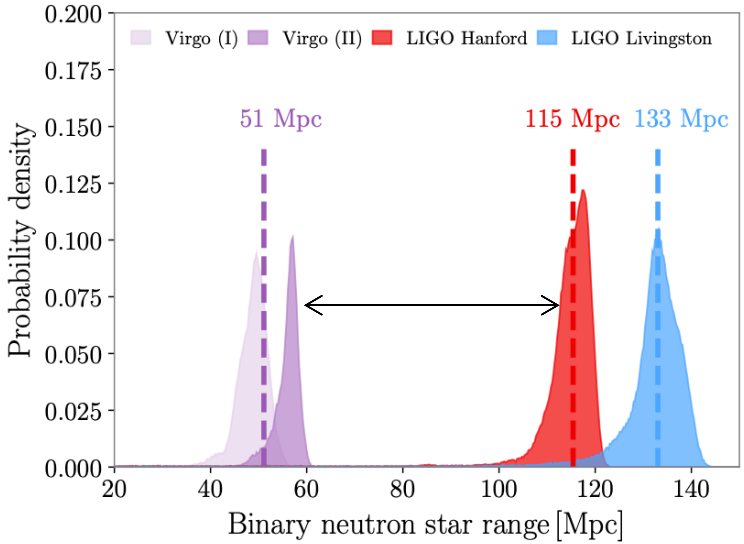
$$\Delta L = \frac{1}{2} h L$$

INCREASE LENGTH
(infrastructure)
€ € €
⏱
Low risk

L x (4/3) → rate x $(4/3)^3$

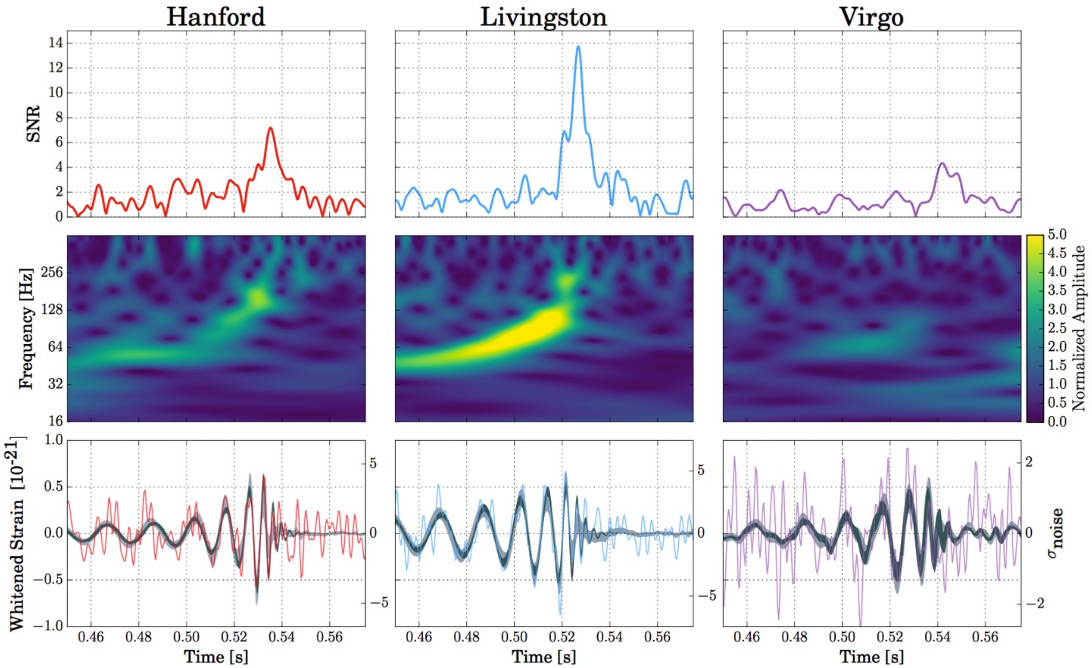
Figure from GWTC-3



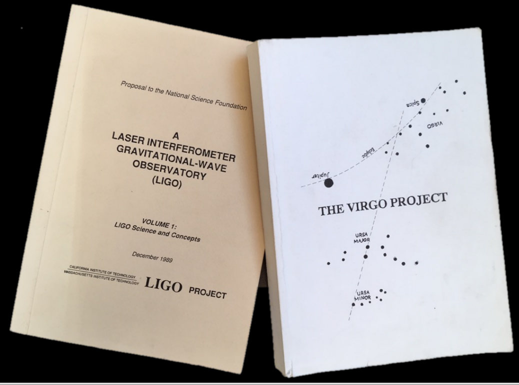


⟷ = combined effect of shorter length and 2 yrs of delay

LOWER SNR

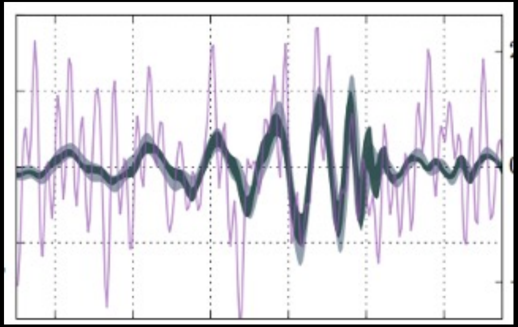


GW170814: Virgo's first event.
Since then, many events but almost all at lower SNR

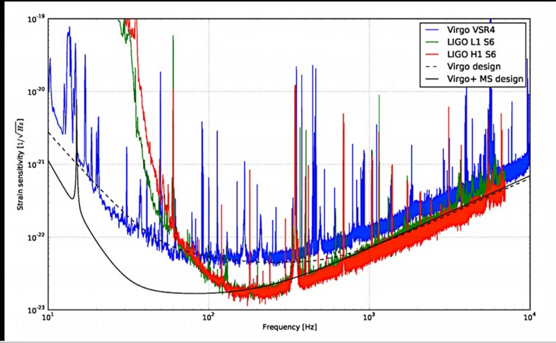


1989: LIGO/Virgo proposal submitted

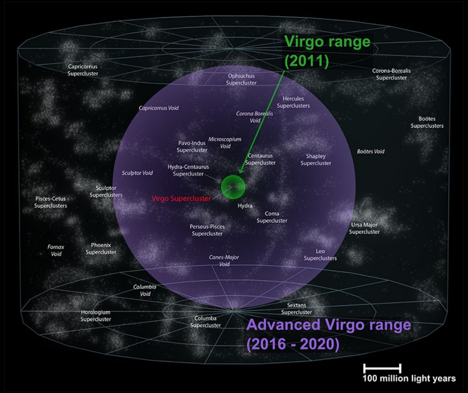
Funding: LIGO 1992, Virgo 1994



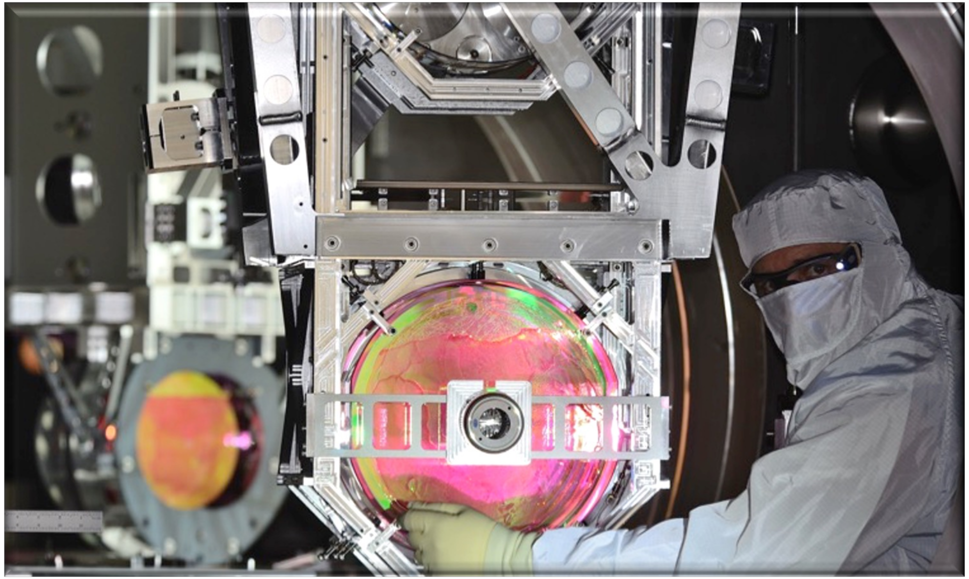
1st signal: LIGO 2015, Virgo 2017



1G design sensitivity: LIGO 2009, Virgo 2011



2G Funding: LIGO 4/2008, Virgo 12/2009



LIGO, SPRING 2013

NETWORK

- Crucial for GW science:
  - Higher reliability
  - Better sky/time coverage
  - Better parameter estimation
  - Better SNR
  - MMA

2007: LSC-VIRGO MoU for a "SINGLE MACHINE"
A MAJOR STEP FORWARD

Memorandum of Understanding

between

VIRGO

on one side

and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

on the other side

Purpose of agreement:

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.

AFT

Pursued by resonant bars since the '80s

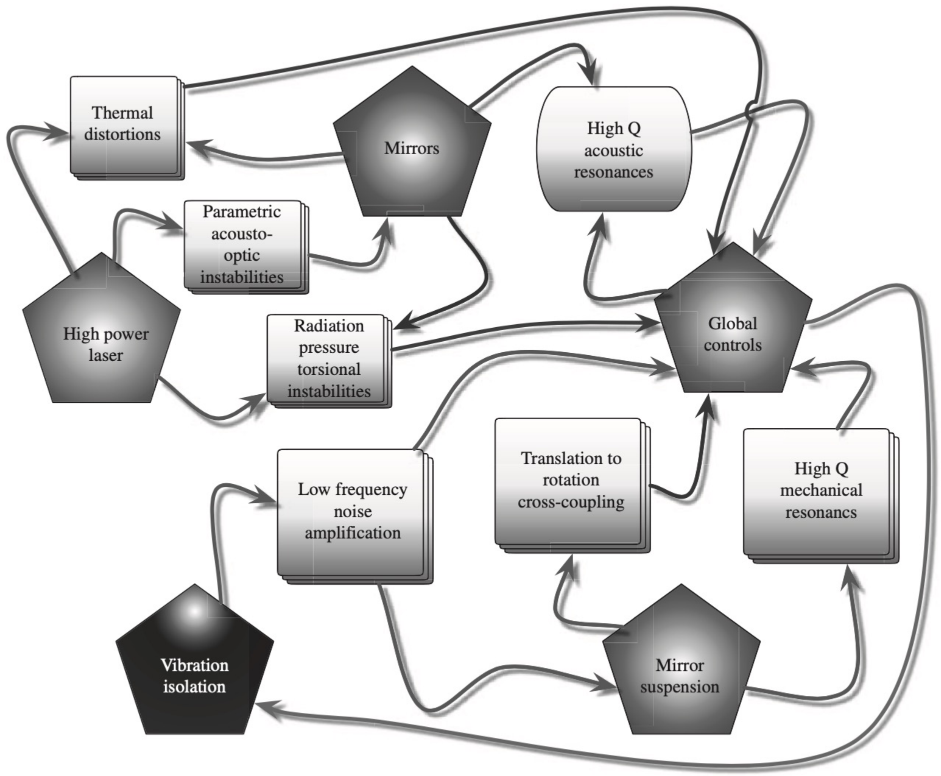
Astron. Astrophys. 216, 325–332 (1989)

ASTRONOMY AND ASTROPHYSICS

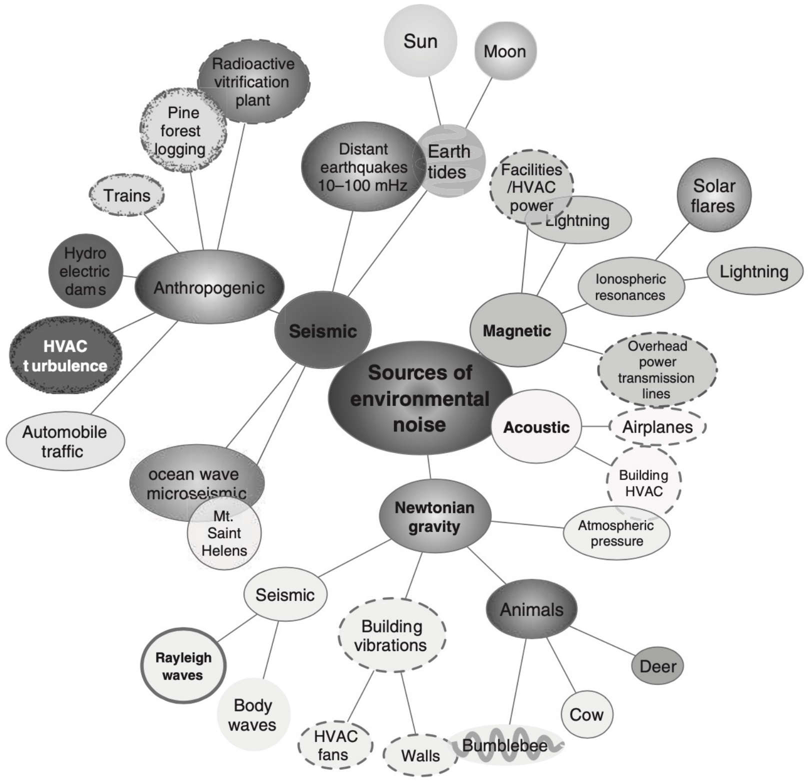
First gravity wave coincidence experiment between resonant cryogenic detectors: Louisiana-Rome-Stanford

E. Amaldi[1,3], O. Aguiar[9], M. Bassan[2,8], P. Bonifazi[3,4], P. Carelli[1,5], M.G. Castellano[3,4], G. Cavallari[7], E. Coccia[2,3], C. Cosmelli[1,3], W.M. Fairbank[8], S. Frasca[1,3], V. Foglietti[3,5], R. Habel[1,6], W.O. Hamilton[9], J. Henderson[8], W. Johnson[9], K.R. Lane[8], A.G. Mann[9], M.S. McAshan[8], P.F. Michelson[8], I. Modena[2,3], G.V. Pallottino[1,3], G. Pizzella[1,3], J.C. Price[8], R. Rapagnani[1,3], F. Ricci[1,3], N. Solomonson[9], T.R. Stevenson[8], R.C. Taber[8], and B.-X. Xu[9]

SIMULATION



The interferometer



The environmental noises

Figure credit: R Adikhari

- The evolution of the simulation complexity and accuracy in the last years has allowed an increasing impact of the simulation effort in the design and understanding of the detectors
- The GW fields still misses a comprehensive simulation program analogous to what exist in HEP
- This effort should be pursued in the next years in the O5/Post-O5/ET perspective and existing detectors are ideal platforms to learn/test/tune the "Geant4" of GW detectors

MAIN MESSAGES

- Invest in length! It's the safest way to sensitivity
- LF is hard: use Virgo as a risk reducer
  - LF noise not fully understood
  - Anthropogenic noise can be an issue also underground
- The simpler the better
  - Complexity adds performance and schedule risks (non-linear!)
  - Invest on infrastructure flexibility for later upgrades
- Network is a crucial aspect of GW science
- Push on a comprehensive simulation effort

There are many more lessons on various topics.

Virgo_nEXT is a great opportunity to test crucial ET technologies on a real (full scale, full complexity) interferometer

SYNERGY is the keyword

LET'S KEEP IN TOUCH!