Advanced Virgo
Status and Perspectives

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On behalf of the Virgo Collaboration

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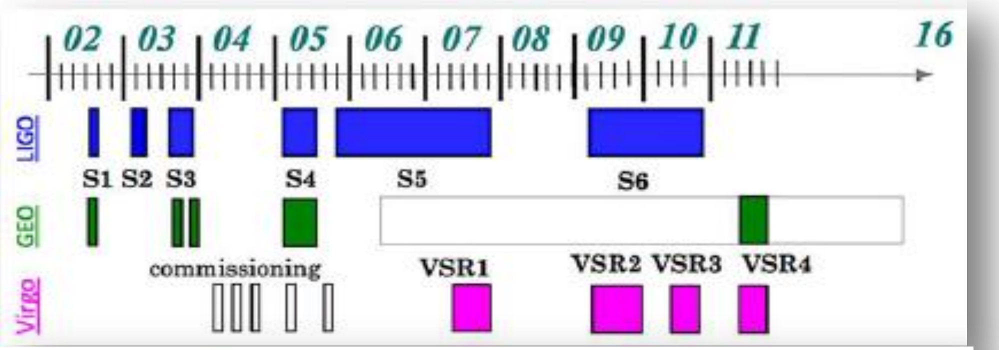
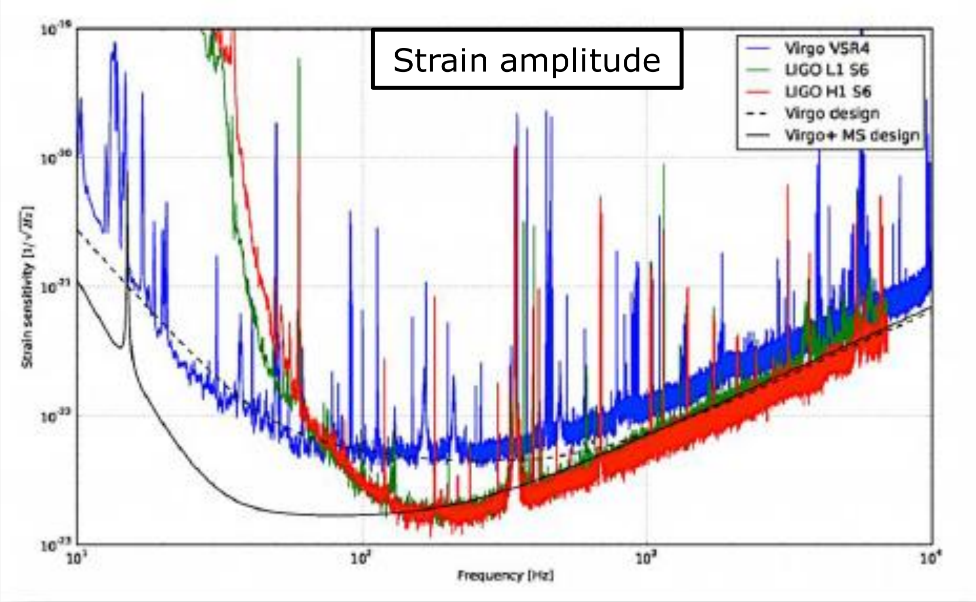
Beyond first generation

1st generation LIGO, Virgo and GEO600 operated for about one decade

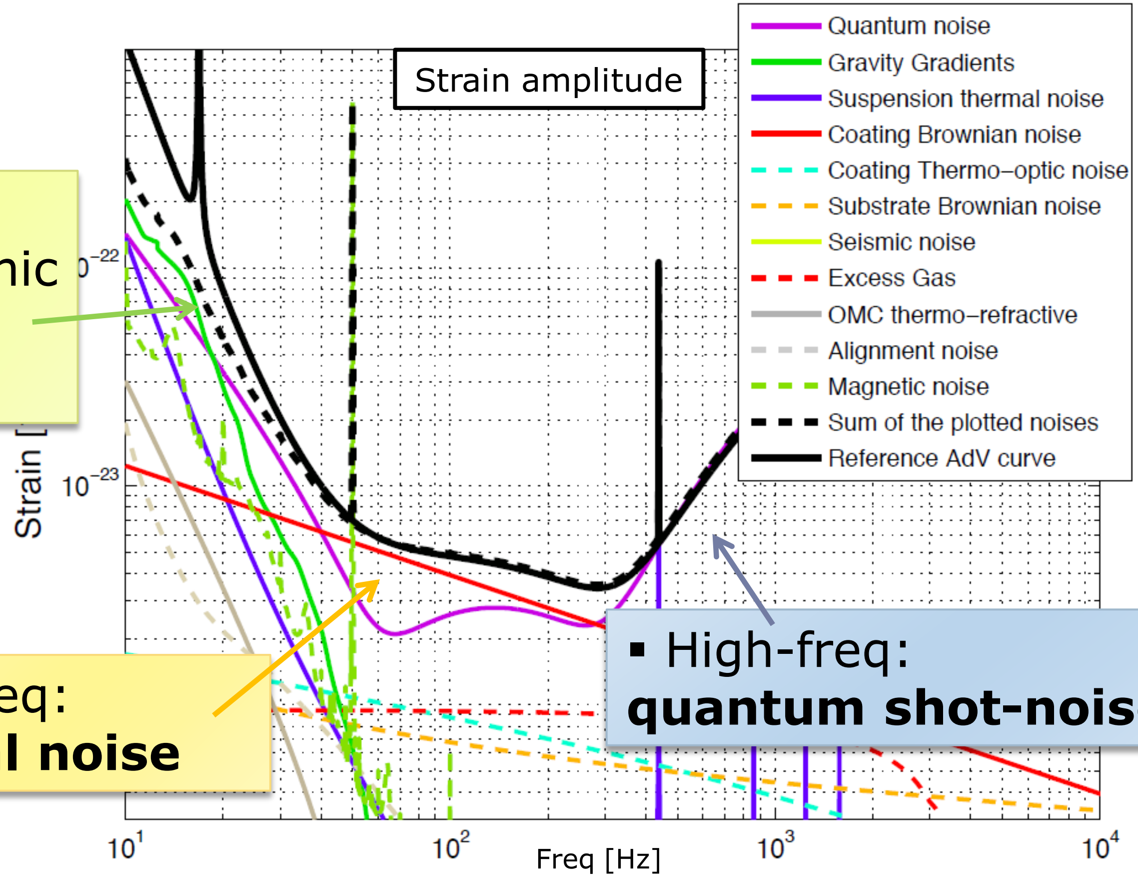
- Demonstrated a reliable technology
    - duty cycle up to 80%, good stationarity of noise
    - good knowledge of limiting noise sources
- ***No detections*** (expected detection rate ~0.01 ev/yrs) but:
    - lots of science produced meanwhile!
    - clear path towards 2nd generation antennas




Strain amplitude

Beyond first generation: design

<u>Limiting noises at different frequency ranges:</u>

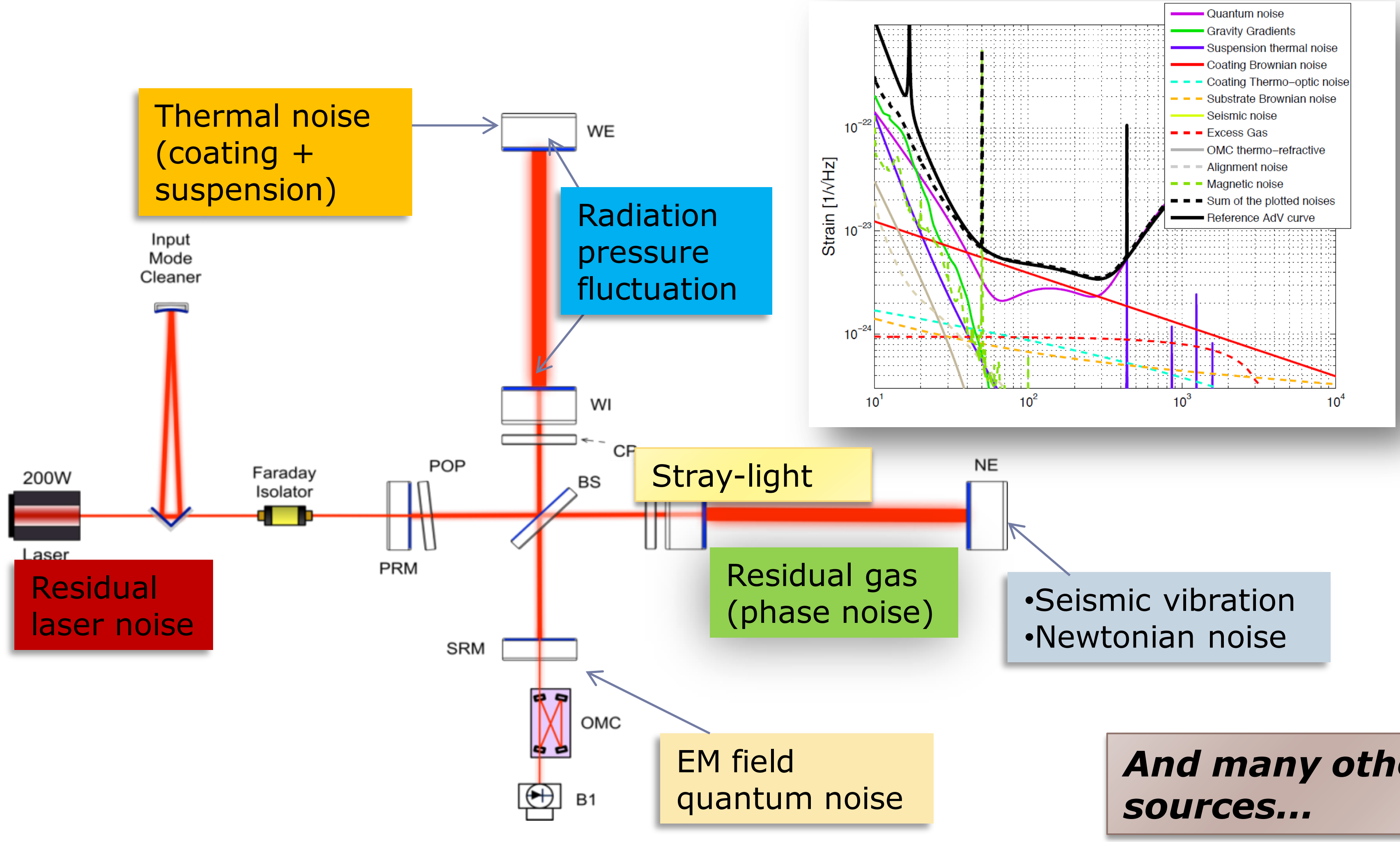


- Low-freq: **newtonian noise**, seismic noise, residual technical noises

- Mid-freq: **thermal noise**

- High-freq: **quantum shot-noise**

Beyond first generation: noise



Thermal noise (coating + suspension)

Radiation pressure fluctuation

Stray-light

Residual laser noise

Residual gas (phase noise)

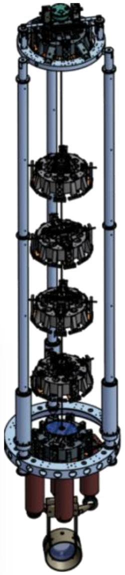
- Seismic vibration
- Newtonian noise

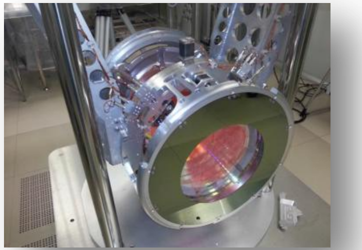
EM field quantum noise

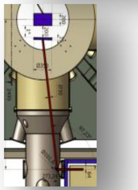
And many other sources…

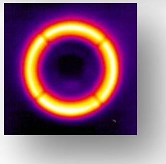
Beyond first generation: actions

- Reducing thermal noise:
  - **increased beam size @ input TM (2.5 x larger)**
  - improved mirrors’ planarity (16 x better)
  - Improved coatings for lower losses (7 x better)
- Reducing quantum noise:
  - Increased finesse of arm cavities (9 x larger than iVirgo, 3 x larger than Virgo+)
  - High power laser (16 x more input power)
  - Heavier test masses (2 x heavier)
- Seismic isolation:
  - iVirgo superattenuators compatible with AdV specs
  - adapted for new payload (added mass and complexity)
  - new electronics
- Thermal compensation (100 x higher power on TM):
  - ring heaters
  - double axicon CO_2 actuators
  - CO_2 central heating
- Better vacuum (10^{-9} mbar instead of 10^{-7})
- Stray light control
  - Suspended optical benches in vacuum
  - New set of baffles

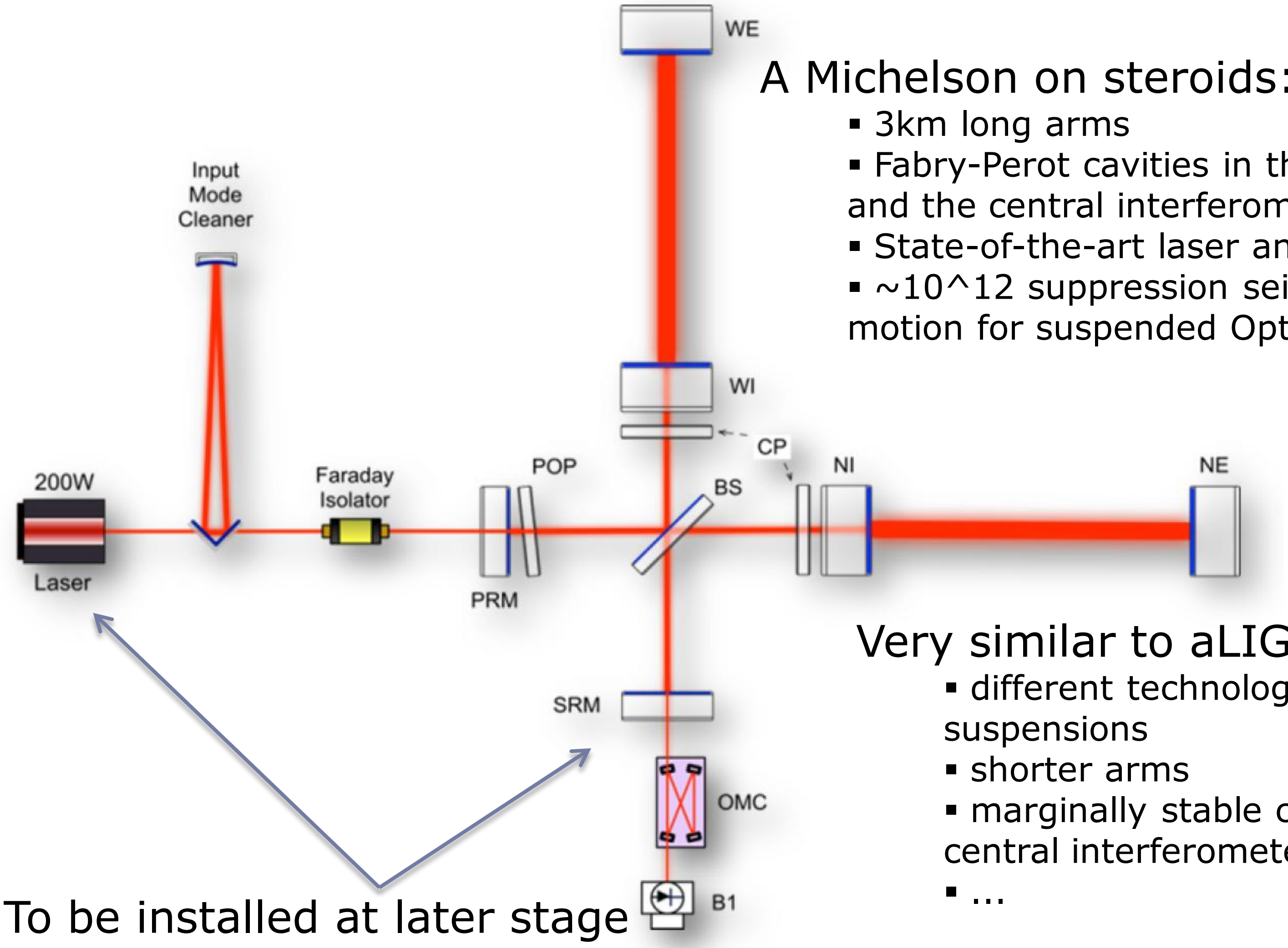








Advanced Virgo design



A Michelson on steroids:

- 3km long arms
- Fabry-Perot cavities in the arms and the central interferometer
- State-of-the-art laser and Optics
- ~10^12 suppression seismic motion for suspended Optics

Very similar to aLIGO but:

- different technology for suspensions
- shorter arms
- marginally stable cavities in central interferometer
- …

To be installed at later stage

Crossing the desert: integration

Integration issues

From design to realization, aka "what *can* go wrong *will* go wrong..."

Many small annoyances and big troubles during the integration phase:

❑ Super-attenuator (>10-years-old) maraging blade failures: inspection of the status of all the blades and replaced 40% of all of them (as a precaution)

❑ One of the suspended optics (compensation plate) was found damaged: dismantled and replaced

❑ ...

❑ Monolithic suspensions failures: a long story…

Integration issues

Monolithic suspensions already demonstrated during VSR3/4 (2010-11):

- we did not expect issues from this side

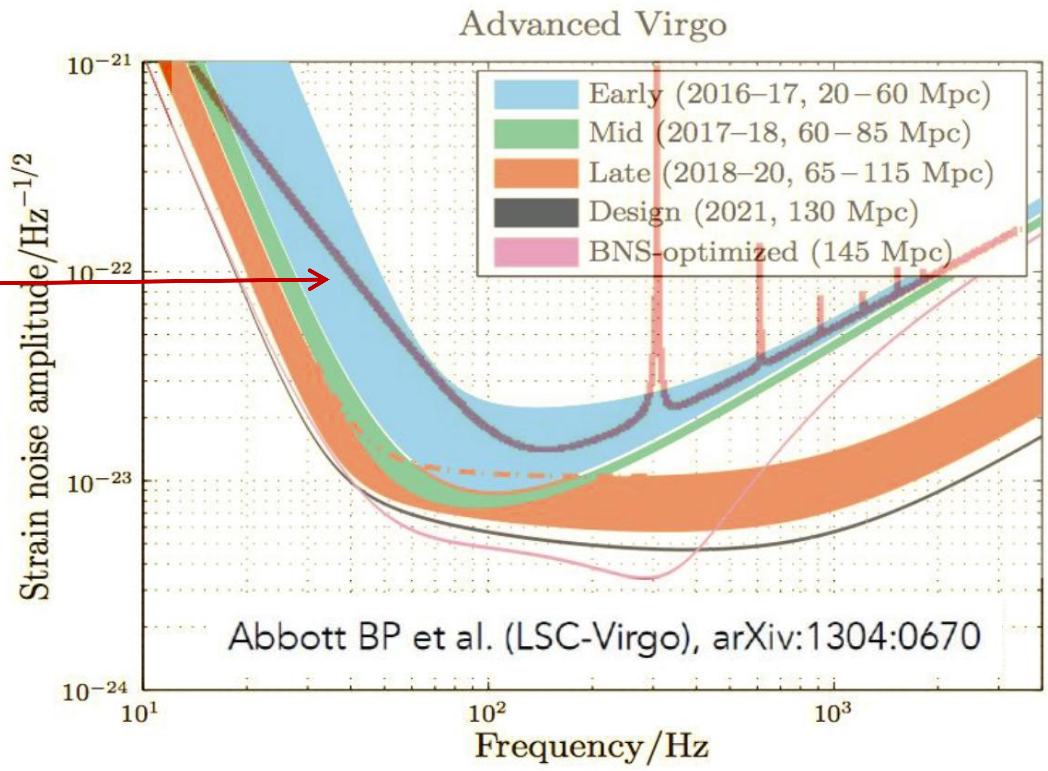
- Repeated breaking of monolithic suspensions under vacuum

- Throughout investigation to find the causes of failure and possible solutions:
  - Failure of glass anchors excluded by microscope analysis of fractures, breaking always occurred at the level of the fibers
  - Basic mechanism of fiber breaking under vacuum eventually identified:
    - fast dust particles hit the fiber and produce fractures
    - in vacuum large velocities are possible, given an initial momentum
    - some pumping/venting cycles using scroll pumps provide non-negligible dust levels in chamber
    - SEM and μ-Raman analysis of dust to understand origin

Integration issues

- Temporary solution for O2 scope: back to steel wires for payloads
  Choice driven by schedule considerations.

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



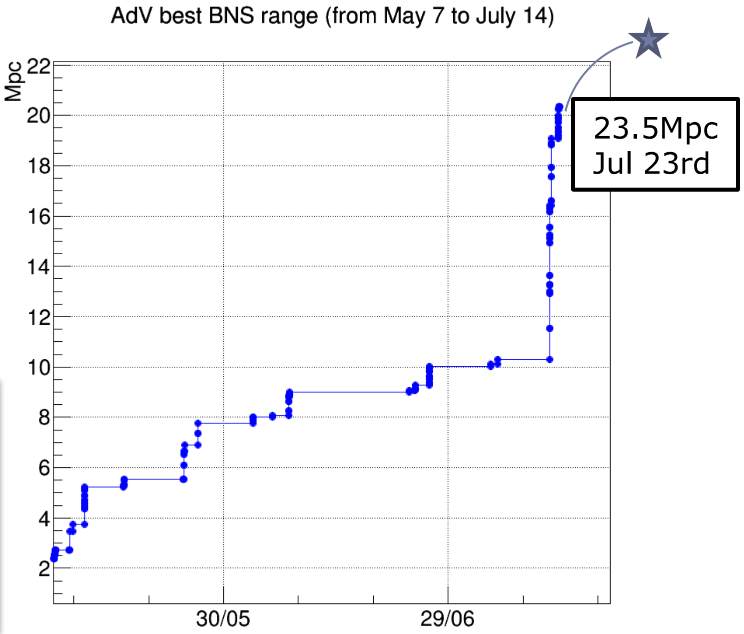
Abbott BP et al. (LSC-Virgo), arXiv:1304:0670

Commissioning

- ❑ Whole interferometer available on Oct 2016
  - First **1hr lock** @ Dark Fringe on March 2017 (***Project Milestone!***)
  - First AdV commissioning run (C8) May 5th to 8th
  - ER11 in June - coincidence with aLIGO:
    - First part from 16 to 19: BNS range ~5-9Mpc, duty cycle ~70%
    - Second part from 23 to 26: BNS range ~8-9Mpc, DC ~80%

- ❑ After ER11:
  - Investigation on stray light
  - Noise injections (magnetic, acoustic, ...)
  - Switch-off tests of selected devices
  - Data Acquisition pipeline and read-out improvement
  - Lock robustness improvement (alignment,...)
  - ...

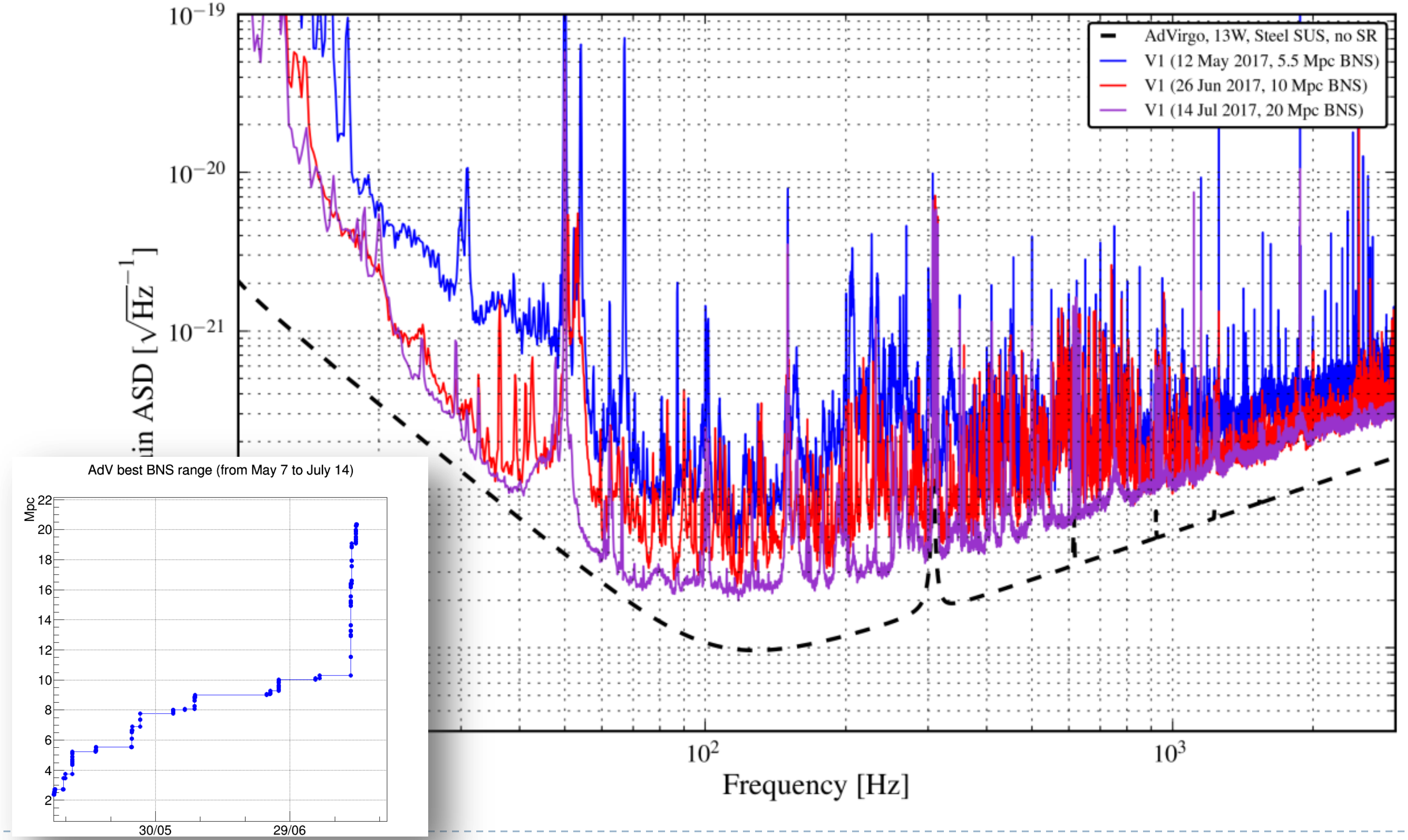
- ❑ Efforts payed off:
  - longest lock segment (so far) ~20hrs
  - "psychological" milestone of beating iVIRGO best sensitivity ***reached***
  - BNS range at ***20Mpc**, and counting...*



23.5Mpc
Jul 23rd

Commissioning

Evolution of strain sensitivity in some 2 months:

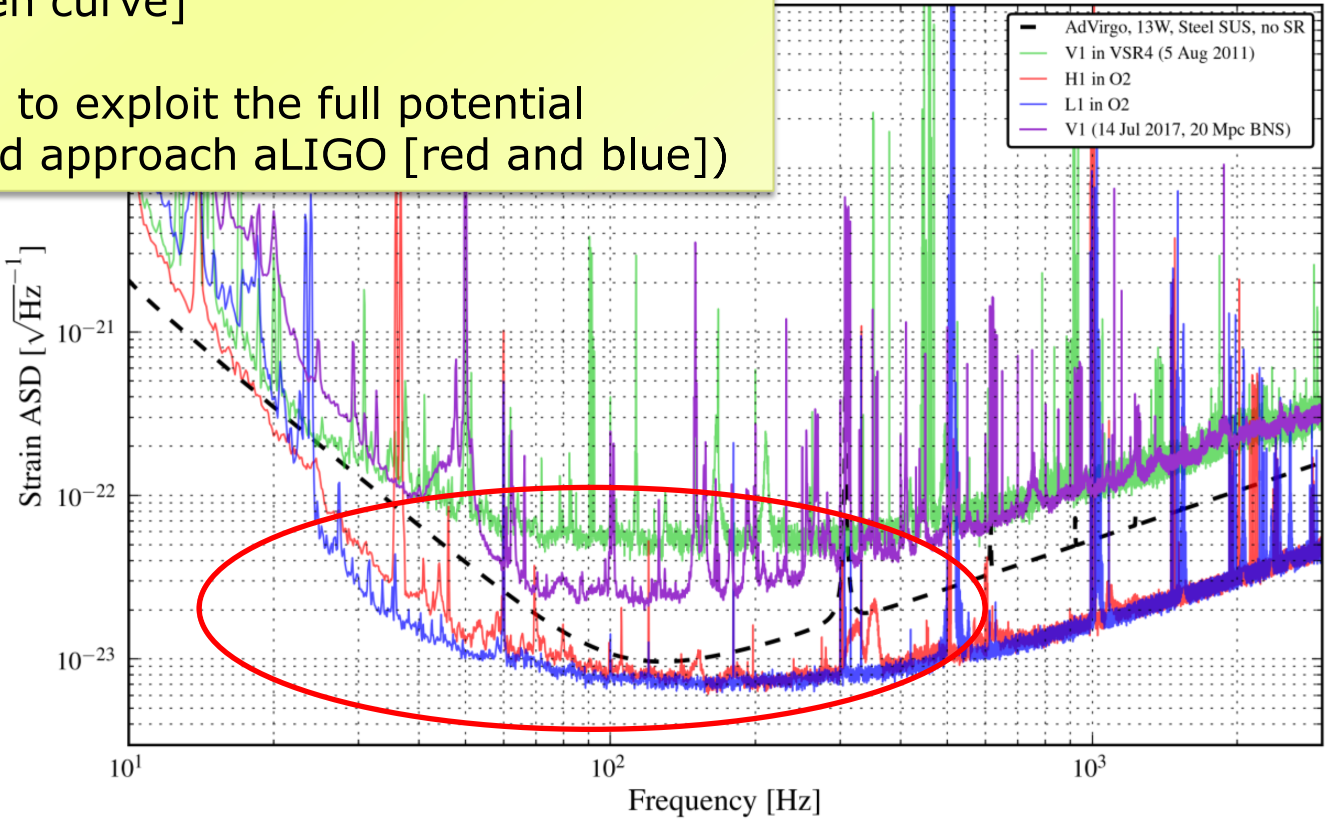


Commissioning

Comparison of current AdV strain sensitivity with relevant references:

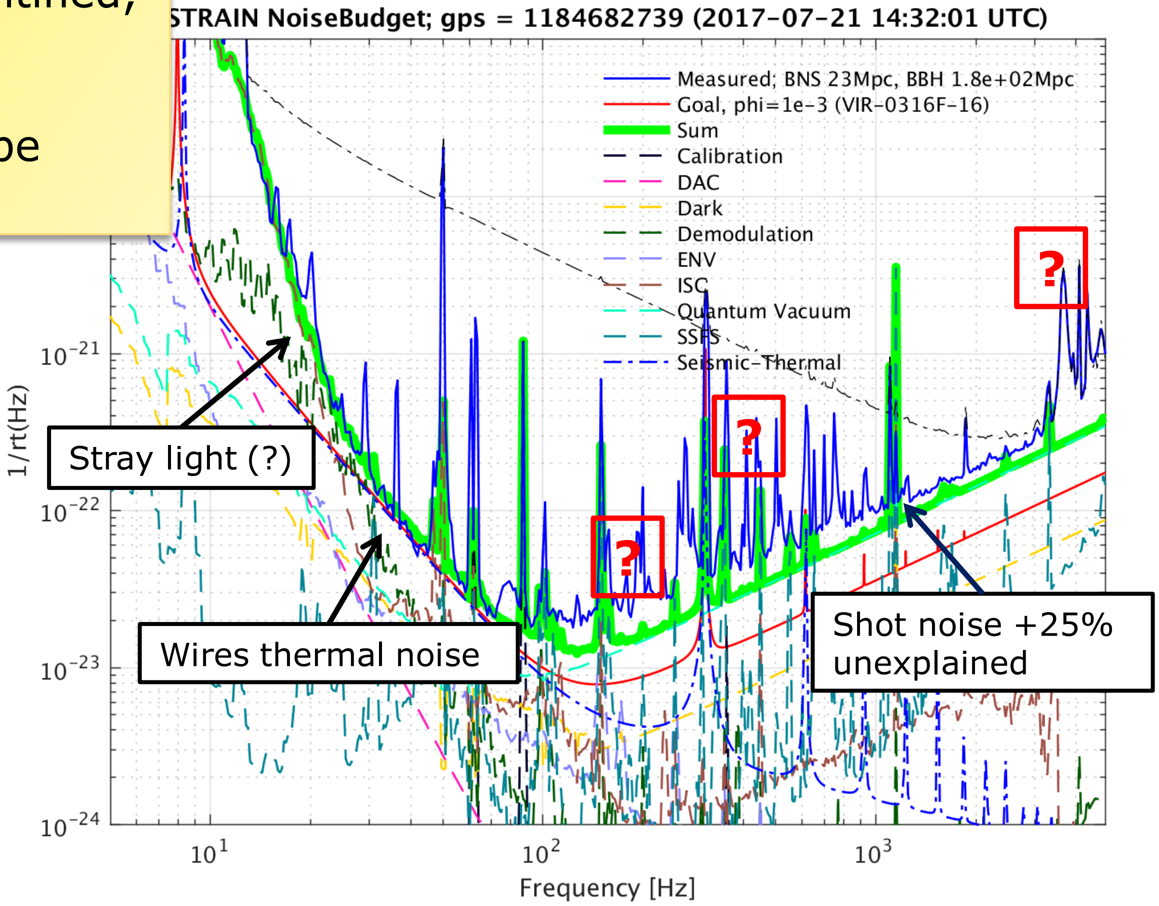
- Current sensitivity [purple curve] better than the best Virgo’s [green curve]

- Still much to do to exploit the full potential [dashed line] (and approach aLIGO [red and blue])



Commissioning

- Noise-budget tool fully working
- Most of the noise sources identified, will be tackled after O2
- Still some “mistery noise” to be understood



Stray light (?)

Wires thermal noise

Shot noise +25% unexplained

Optical characterization

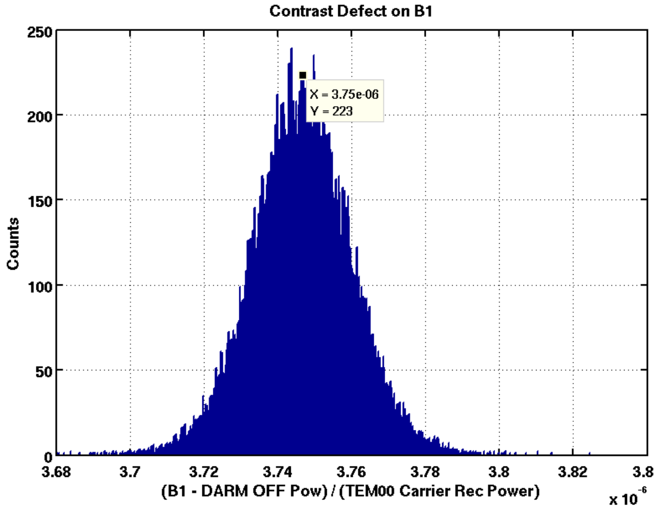
Extensive measurement campaign to characterize optical parmaters

Recycling gains in PR cavity

	Expected	Measured
Carrier	41	36-39
6 MHz	77	~ 40
56 MHz	13	~12

- Carrier and sidebands recycling gains:
  - Carrier and 56 MHz close to design value;
  - 6 MHz sideband around 50% (for all modes) as expected from simulations;
- Arm cavities characterization:
  - RTL reasonable (<75ppm) and not too much unbalanced;
  - Finesse as nominal;
  - Very low Finesse asymmetry;
  - Low contrast defect ~4 ppm;

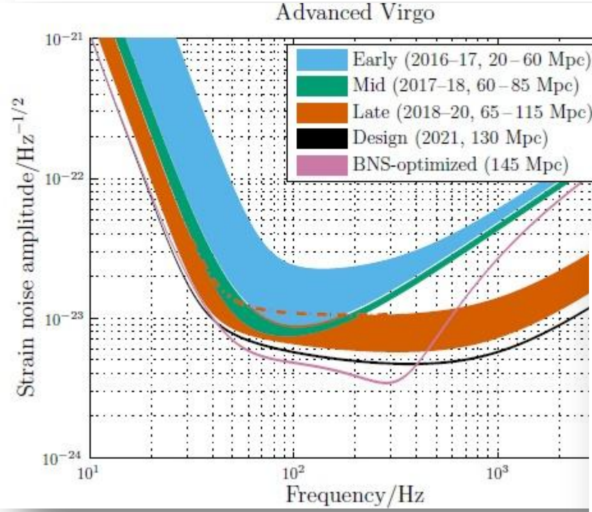
	RTL	Finesse
North	~ 60 ppm	461±6
West	~ 54 ppm	464±6



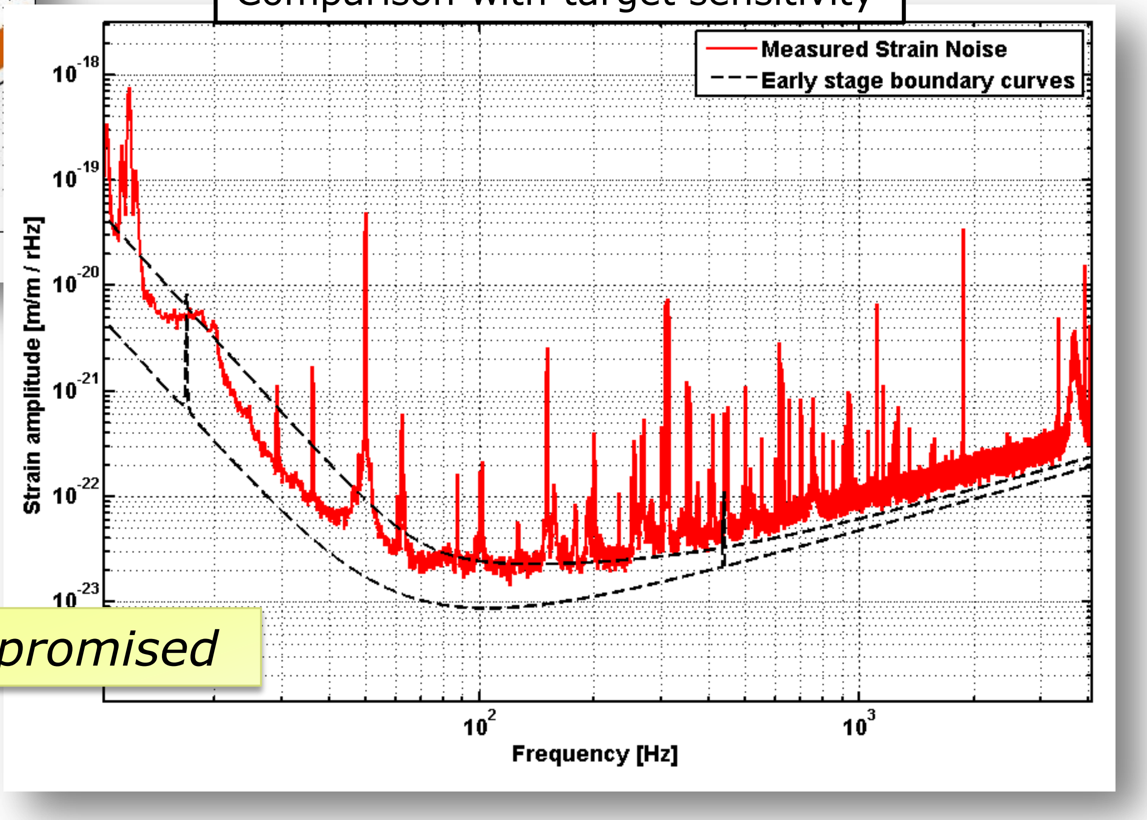
The Optical parameters are very close to nominal

Where do we stand?

Abbott BP et al. (LSC-Virgo), arXiv:1304:0670



Comparison with target sensitivity



Very close to what we promised

Summary and perspectives

☐ Advanced Virgo is now fully operational:

- Monolithic suspension replaced with metallic wires to increase reliability – but origin of the failing understood
- Optical parameters close to nominal values
- Lock acquisition robust and reliable (lock segments ~tens of hrs)
- Strain sensitivity close to “early-stage” target
- Most of the limiting noise sources identified

☐ We will go through data-taking (hopefully O2) and then:

- Vacuum system upgrade for dust protection
- Monolithic suspensions re-installation
- High Power laser installation
- More noise-hunting (stray light issues, data-acquisition hardware configuration, ...)
- Parameters tuning with thermal compensation system

...To be ready for O3

Thank you

Extra Slides

Advanced Virgo

In a nutshell:

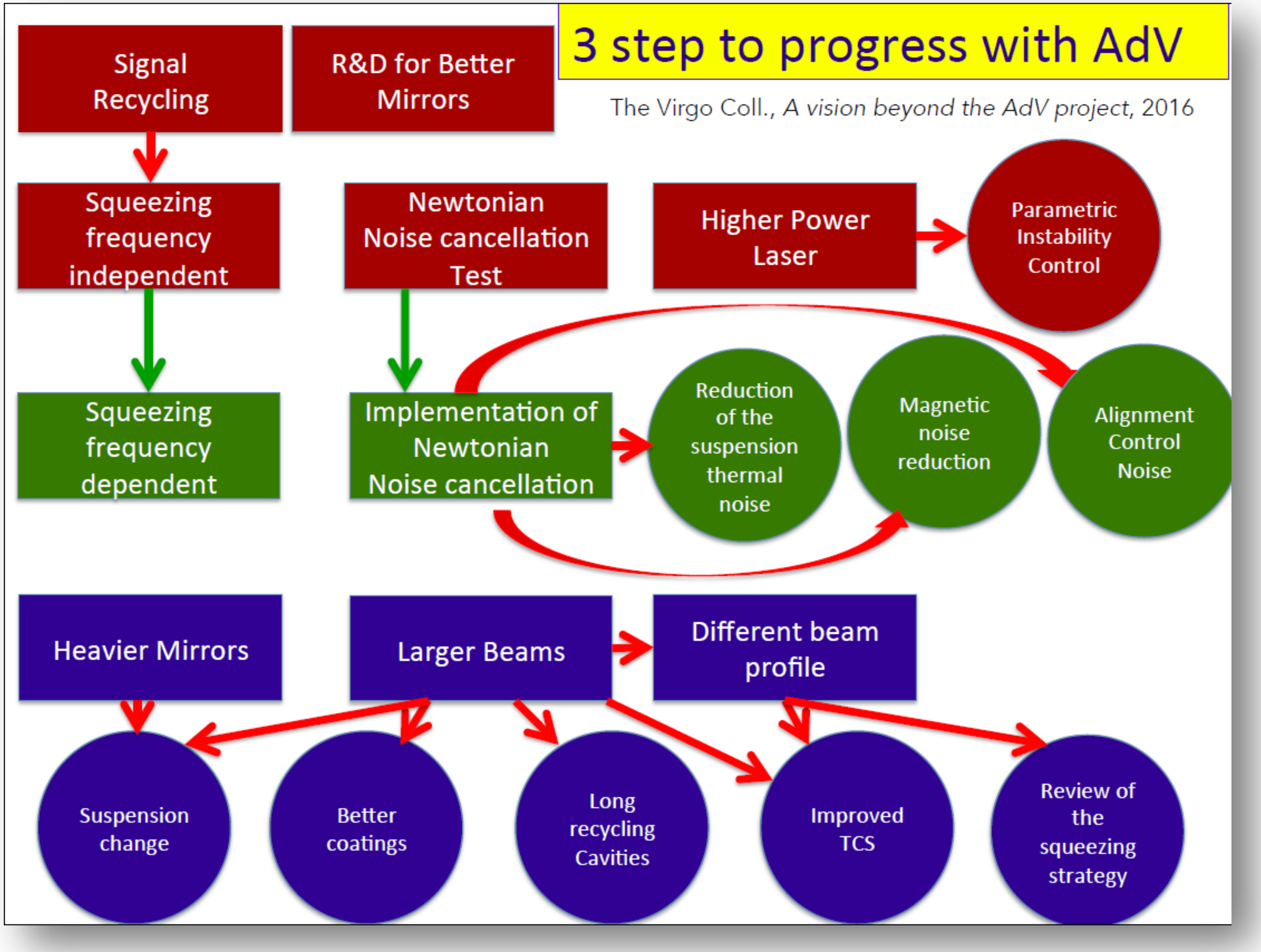
- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Hungary, Poland, Spain
- Funding approved in Dec 2009
- Part of a larger collaboration with LIGO: LVC
- First science data scheduled in 2017

http://public.virgo-gw.eu/)

6 European countries
20 labs, ~250 authors

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest
Univ. Of Valencia

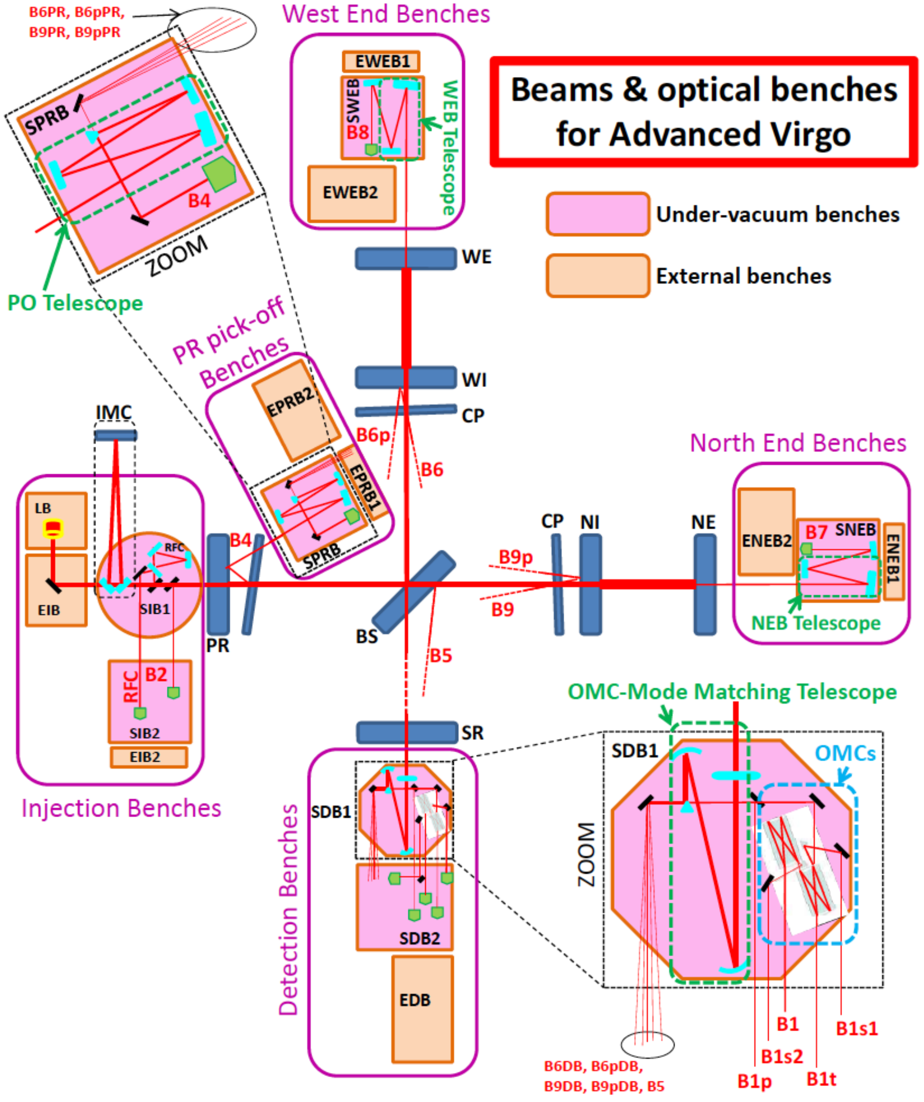
Beyond AdV



3 step to progress with AdV

The Virgo Coll., *A vision beyond the AdV project*, 2016

AdV setup

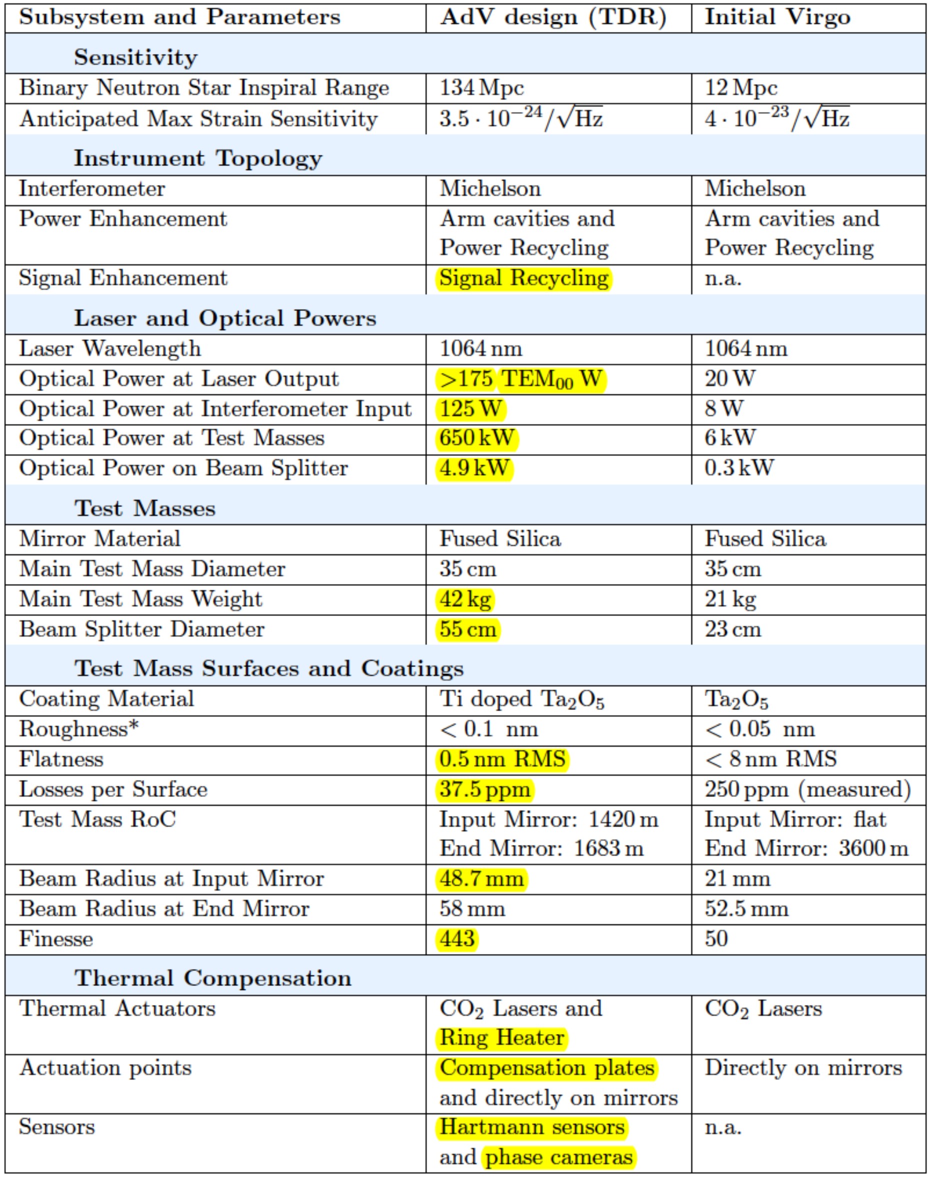


Beams & optical benches for Advanced Virgo

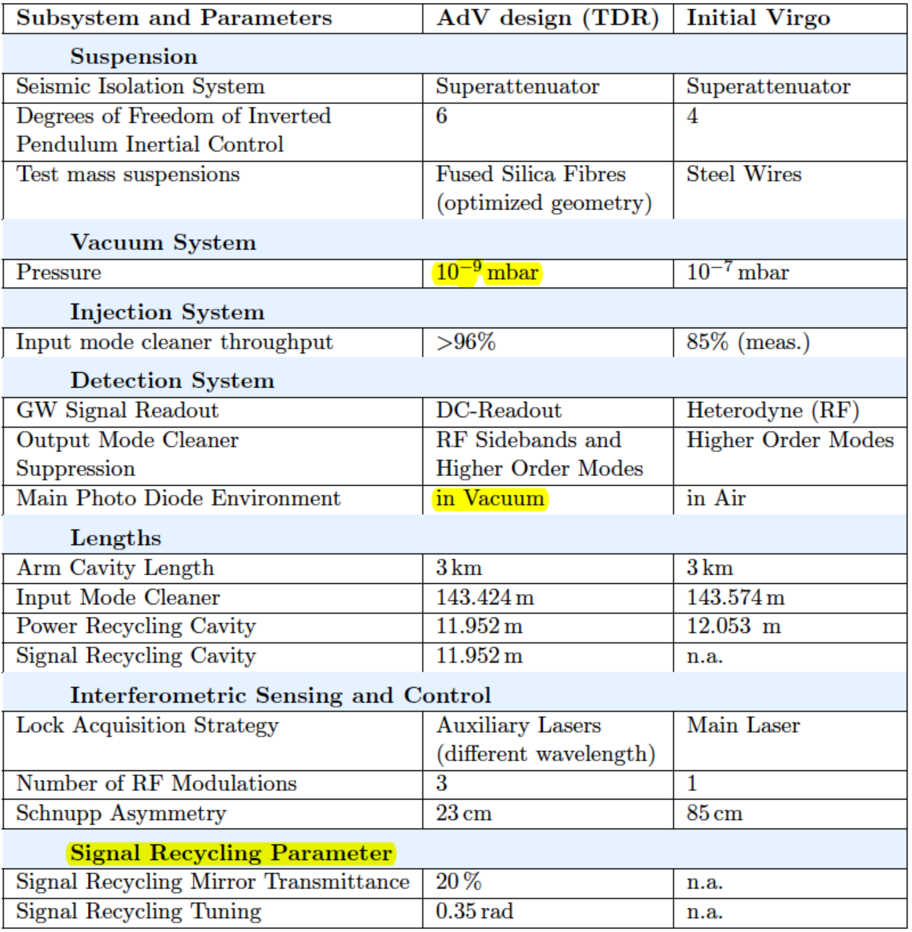
🟪 Under-vacuum benches

🟧 External benches

AdV vs initial Virgo



Subsystem and Parameters	AdV design (TDR)	Initial Virgo
Sensitivity		
Binary Neutron Star Inspiral Range	134 Mpc	12 Mpc
Anticipated Max Strain Sensitivity	$3.5 \cdot 10^{-24}/\sqrt{\mathrm{Hz}}$	$4 \cdot 10^{-23}/\sqrt{\mathrm{Hz}}$
Instrument Topology		
Interferometer	Michelson	Michelson
Power Enhancement	Arm cavities and Power Recycling	Arm cavities and Power Recycling
Signal Enhancement	Signal Recycling	n.a.
Laser and Optical Powers		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	>175 TEM$_{00}$ W	20 W
Optical Power at Interferometer Input	125 W	8 W
Optical Power at Test Masses	650 kW	6 kW
Optical Power on Beam Splitter	4.9 kW	0.3 kW
Test Masses		
Mirror Material	Fused Silica	Fused Silica
Main Test Mass Diameter	35 cm	35 cm
Main Test Mass Weight	42 kg	21 kg
Beam Splitter Diameter	55 cm	23 cm
Test Mass Surfaces and Coatings		
Coating Material	Ti doped Ta$_2$O$_5$	Ta$_2$O$_5$
Roughness*	< 0.1 nm	< 0.05 nm
Flatness	0.5 nm RMS	< 8 nm RMS
Losses per Surface	37.5 ppm	250 ppm (measured)
Test Mass RoC	Input Mirror: 1420 m End Mirror: 1683 m	Input Mirror: flat End Mirror: 3600 m
Beam Radius at Input Mirror	48.7 mm	21 mm
Beam Radius at End Mirror	58 mm	52.5 mm
Finesse	443	50
Thermal Compensation		
Thermal Actuators	CO$_2$ Lasers and Ring Heater	CO$_2$ Lasers
Actuation points	Compensation plates and directly on mirrors	Directly on mirrors
Sensors	Hartmann sensors and phase cameras	n.a.



Subsystem and Parameters	AdV design (TDR)	Initial Virgo
Suspension		
Seismic Isolation System	Superattenuator	Superattenuator
Degrees of Freedom of Inverted Pendulum Inertial Control	6	4
Test mass suspensions	Fused Silica Fibres (optimized geometry)	Steel Wires
Vacuum System		
Pressure	10^{-9} mbar	10^{-7} mbar
Injection System		
Input mode cleaner throughput	>96%	85% (meas.)
Detection System		
GW Signal Readout	DC-Readout	Heterodyne (RF)
Output Mode Cleaner Suppression	RF Sidebands and Higher Order Modes	Higher Order Modes
Main Photo Diode Environment	in Vacuum	in Air
Lengths		
Arm Cavity Length	3 km	3 km
Input Mode Cleaner	143.424 m	143.574 m
Power Recycling Cavity	11.952 m	12.053 m
Signal Recycling Cavity	11.952 m	n.a.
Interferometric Sensing and Control		
Lock Acquisition Strategy	Auxiliary Lasers (different wavelength)	Main Laser
Number of RF Modulations	3	1
Schnupp Asymmetry	23 cm	85 cm
Signal Recycling Parameter		
Signal Recycling Mirror Transmittance	20 %	n.a.
Signal Recycling Tuning	0.35 rad	n.a.

From AdV TDR
https://tds.ego-gw.it/?content=3&r=9317