Virgo Interferometer: towards and beyond the O3 science run

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Gravitational Wave group

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Utrecht, 18/12/2018

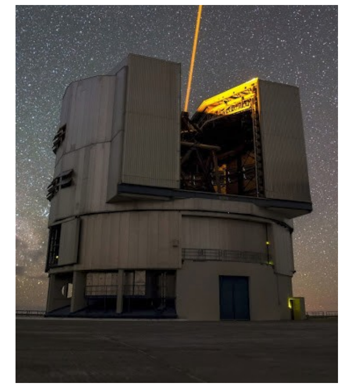
Advanced Virgo

Nikhef

Still newcomers in astronomy

- Optical telescopes: 400 years of progress since first detection

Galileo (1609) Yerkes (1895) VLT (1998) Hubble (1990)



- GW detection: 50 years of experiments, first detection only in 2015

Weber (1968) CalTech (1983) Virgo/LIGO (~2000) LISA (2034)

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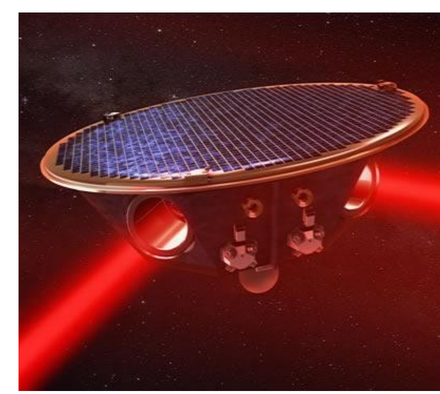
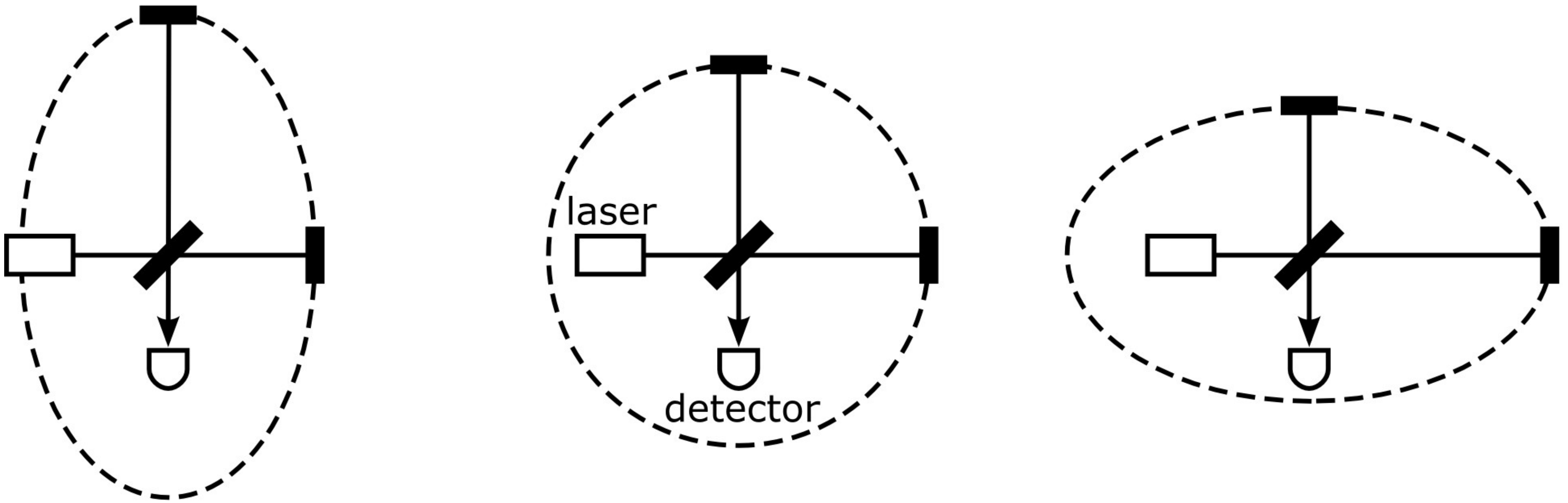


Interferometric detection

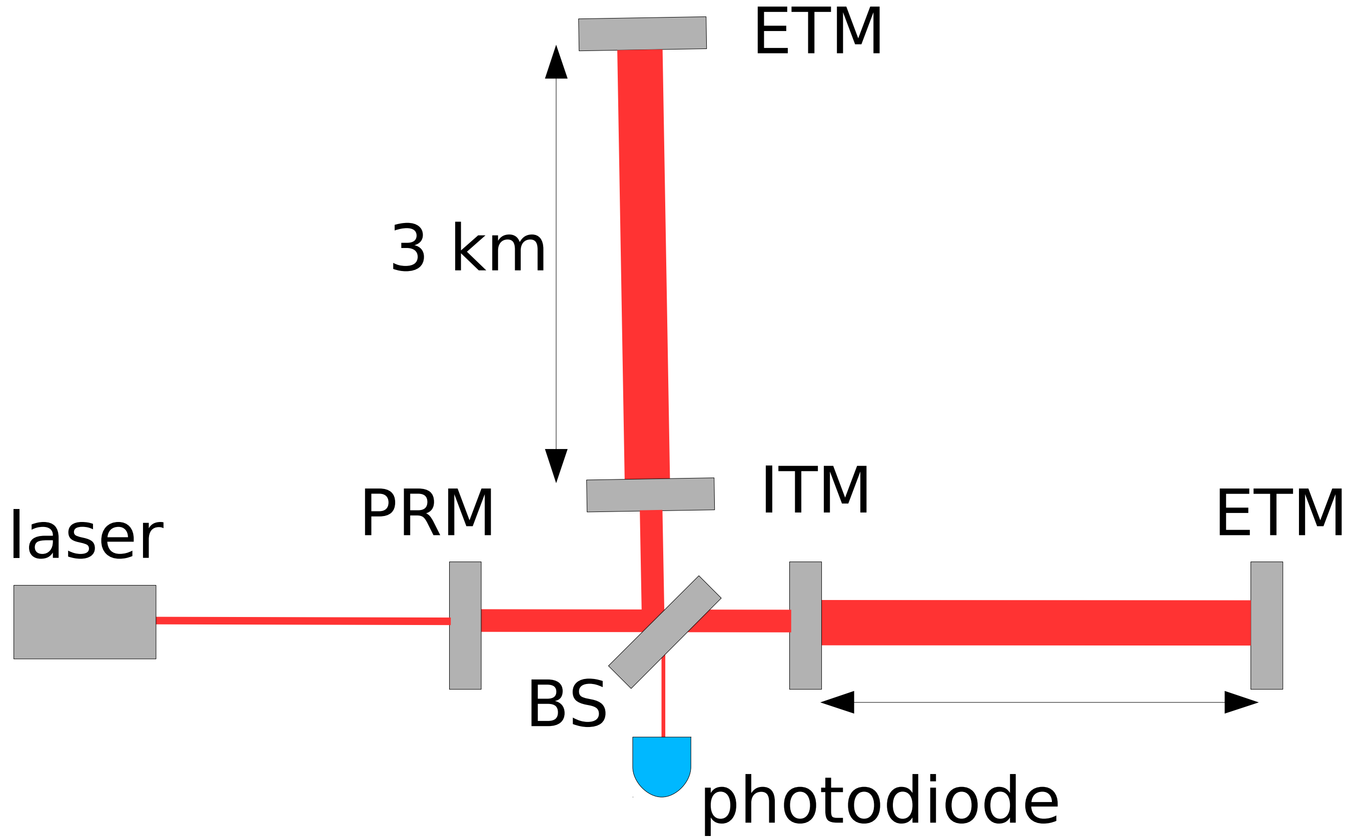


- Michelson interferometer is a natural fit for measuring gravitational waves: differential effect for orthogonal arms. Omni-directional sensitivity (with antenna pattern)
- Interferometers measure strain **amplitude**: signal scales as 1 / distance

Virgo Interferometer

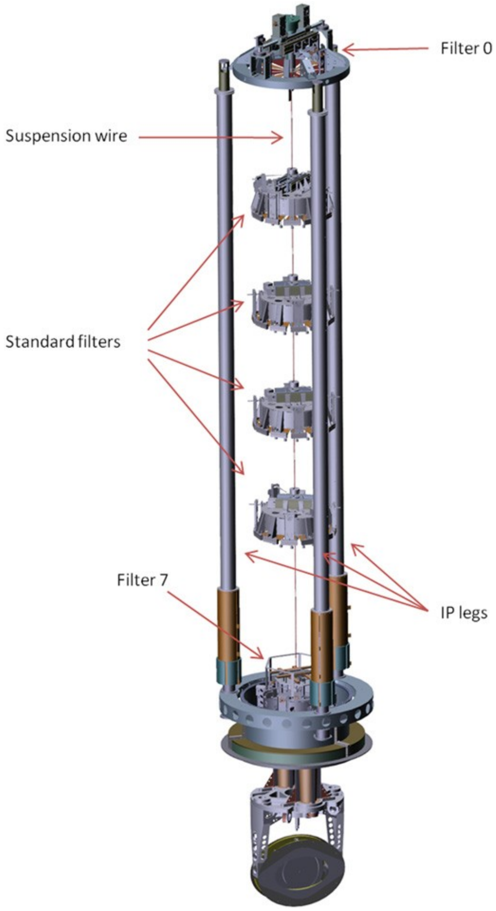
- 3 x 3 km interferometer, located near Pisa, Italy
- Originally a French-Italian collaboration, now about 200 scientists from Italy, France, Netherlands (Nikhef), Poland, Hungary, Spain
- Operating in a network with two LIGO interferometers in the US

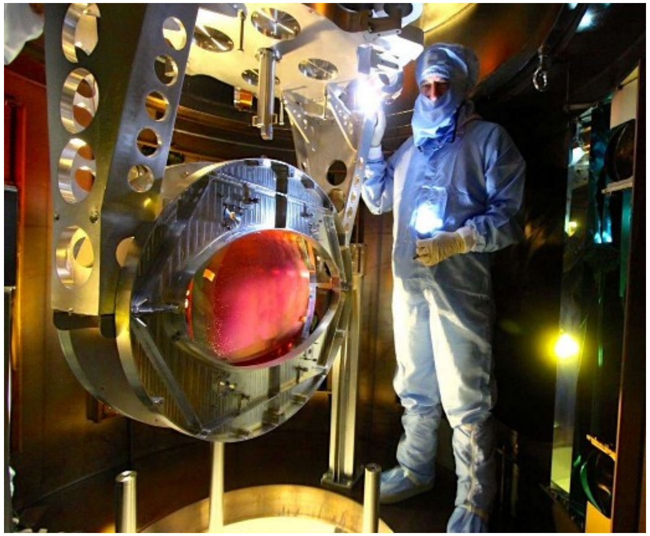
Optical scheme

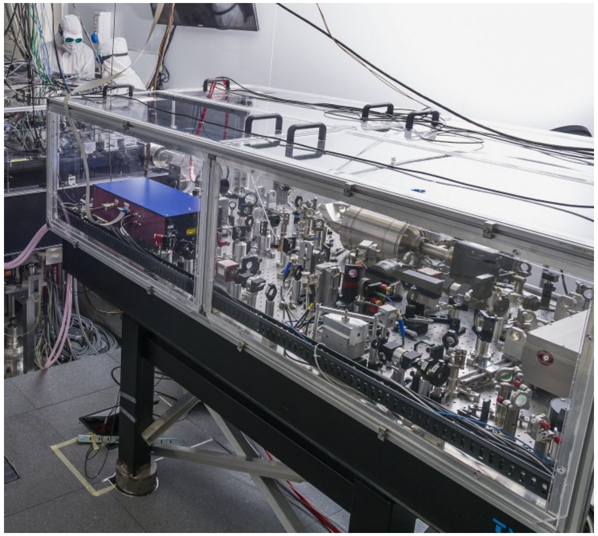


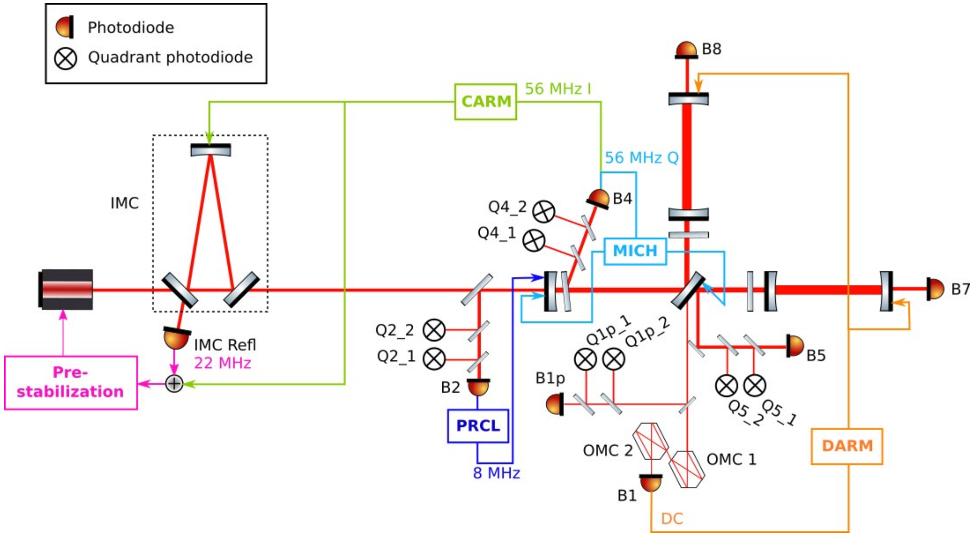
- 3 km Michelson interferometer, tuned to dark-fringe for SNR reasons
- Add Fabry-Perot cavities in the long arms to increase effective arm length to 800 km
- Add a Power Recycling Mirror, to increasing the laser power by a factor 37
- Power in central cavities ~500 W, power in long arm cavities ~100 kW

Advanced Virgo upgrade



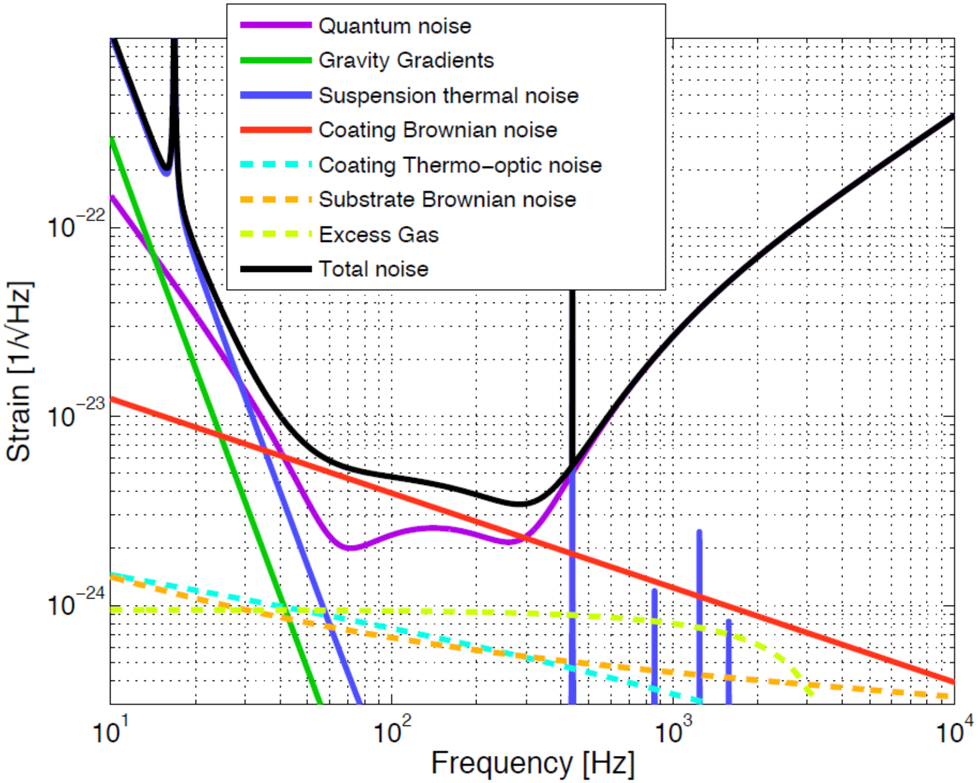


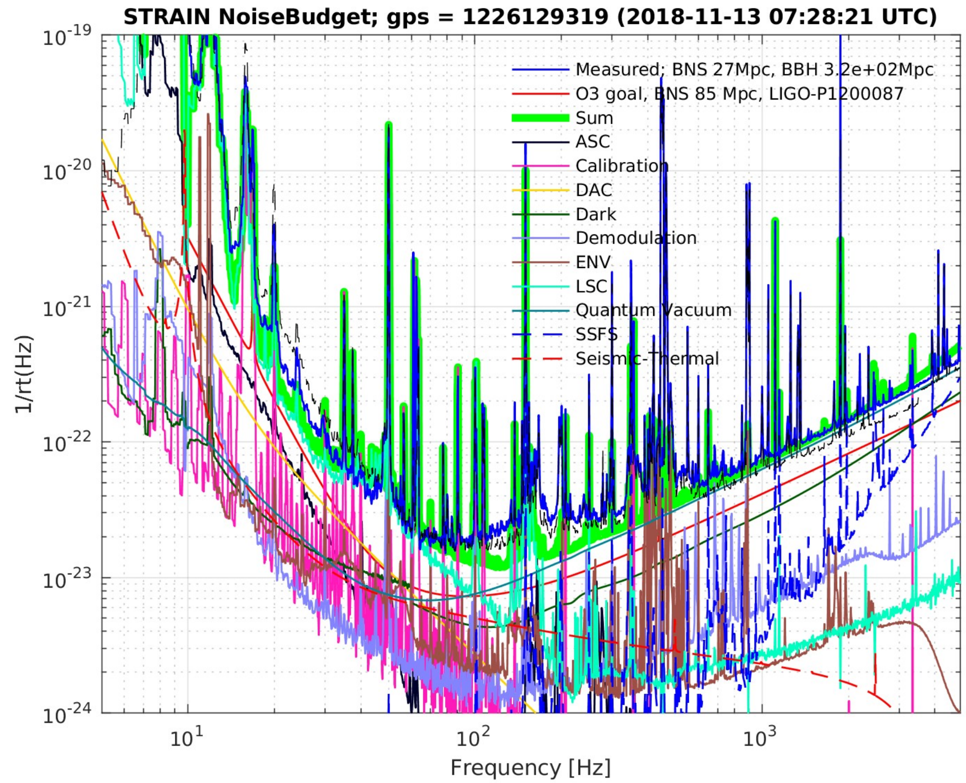




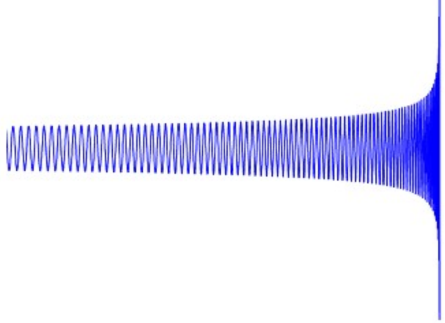
- High power lasers, seismic isolation, low loss optics, ultra-high vacuum, real-time controls

Noise sources

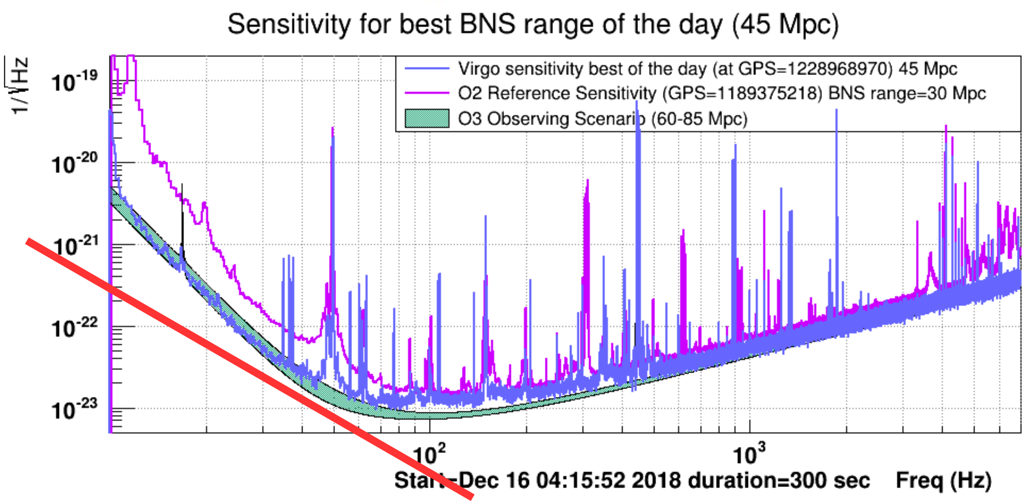


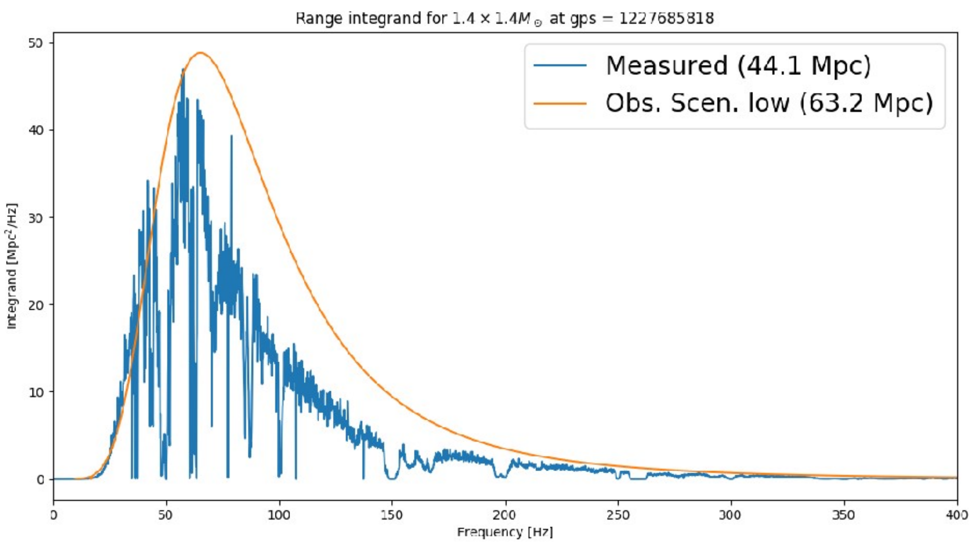


- Noise budget dominated by **fundamental noises** that are hard to change
  - quantum noise, coating/suspension thermal noise, residual gas absorption
- Also various **technical noises** like coupling to environmental noise (magnetic, acoustic, seismic), scattered light, ADC/DAC/electronics noise, ... Takes many years of commissioning to resolve all of these



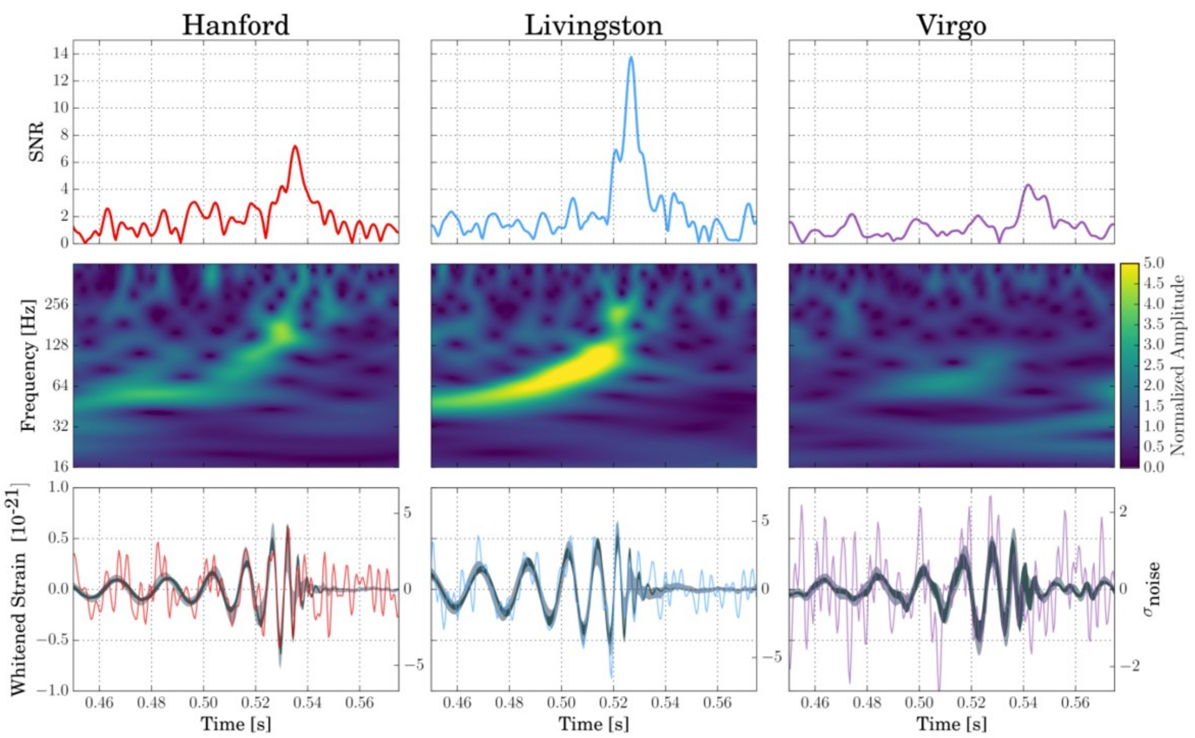
It is all about the range!

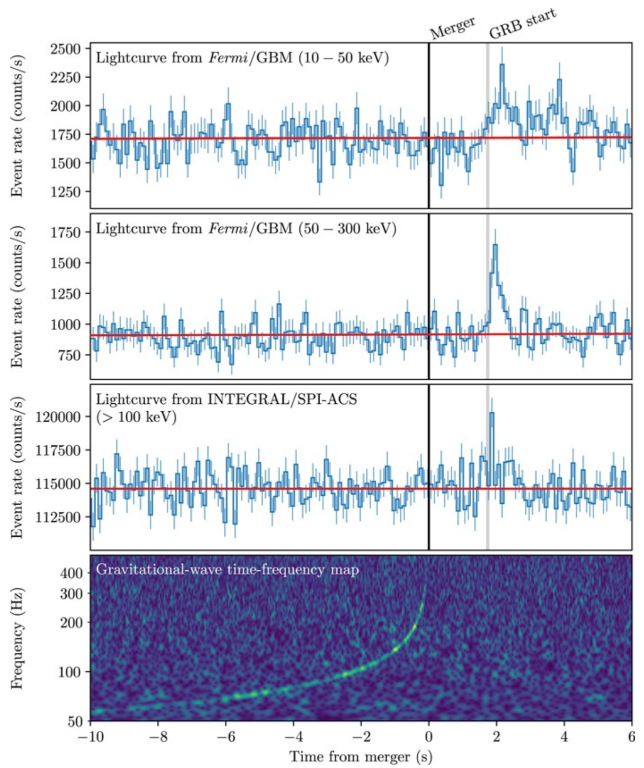




- All GW detections so far are from binary inspirals: chirped GW signal that increases in frequency and amplitude until the system merges
- **Range**: sky averaged distance (in megaparsec) to which we can detect a model system with an SNR of 8, typically a binary with 2x 1.5 solar masses. Detection rate ~ range^3
- Signal is recovered by matched filtering: more SNR is accumulated at lower frequencies, since that is where the signal spends more time
- $$\text{range} = C(m_1, m_2)\sqrt{\int_0^{f\max(m_1,m_2)} \frac{f^{-7/3}}{\text{PSD}(f)} df}$$

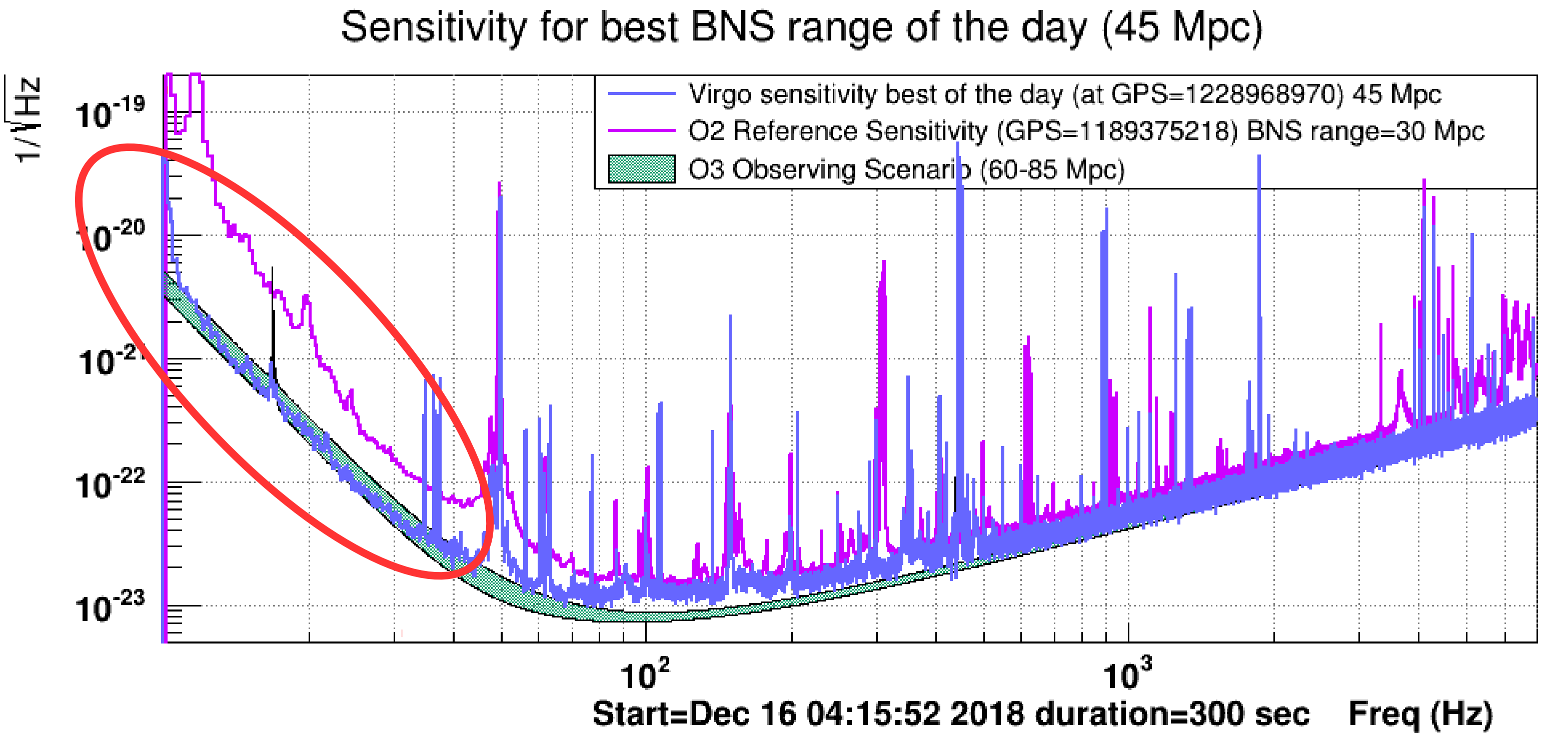
O2 science run: first detections by Advanced Virgo





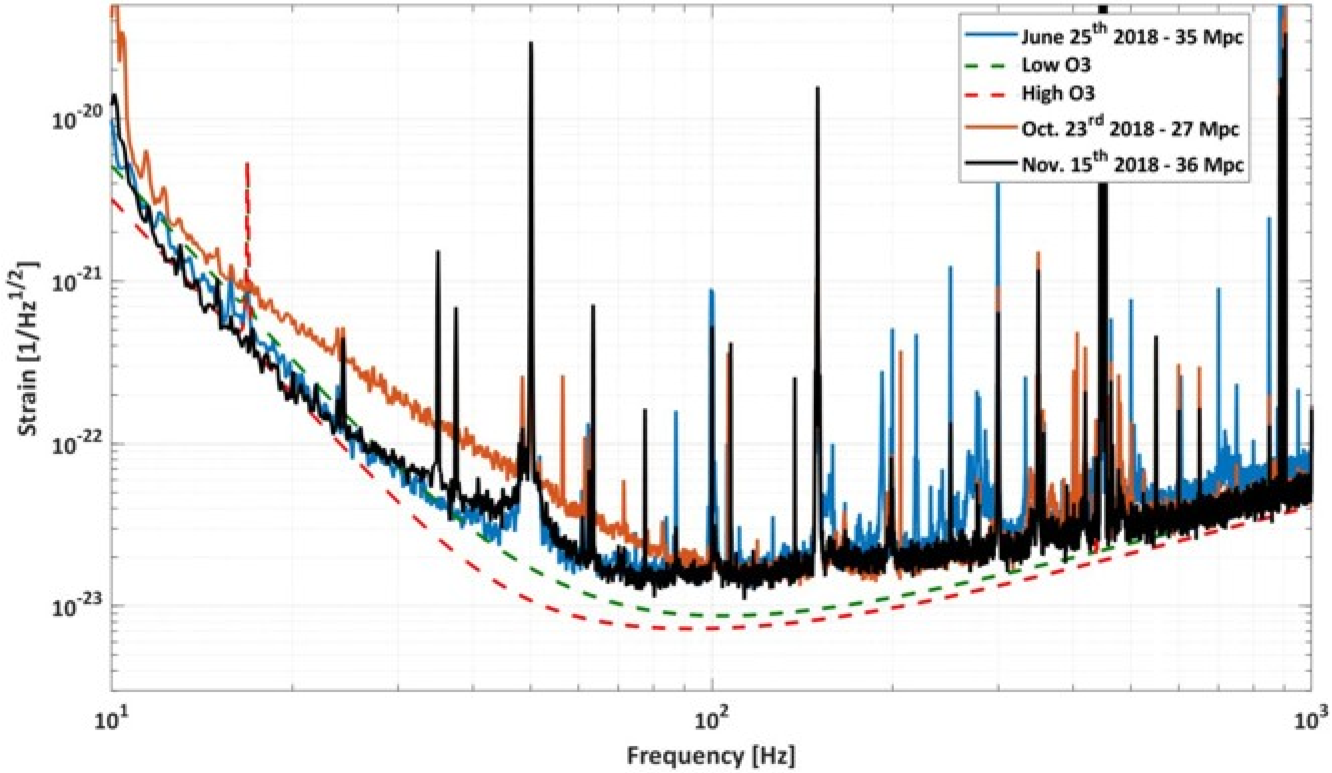
- 2015: Advanced LIGO did Observation Run 1 (O1) by themselves: first 3 detections
- Meanwhile, Virgo was struggling to finish the Advanced Virgo upgrade:
  major problem with repeated breaking of monolithic fibers, temporarily used metal wires
- LIGO started O2 end of 2016, Virgo joined in August 2017 with range of ~30 Mpc
- Very successful period: 2 binary black hole, 1 binary neutron star merger (with GRB, optical afterglow!)

Monolithic suspensions



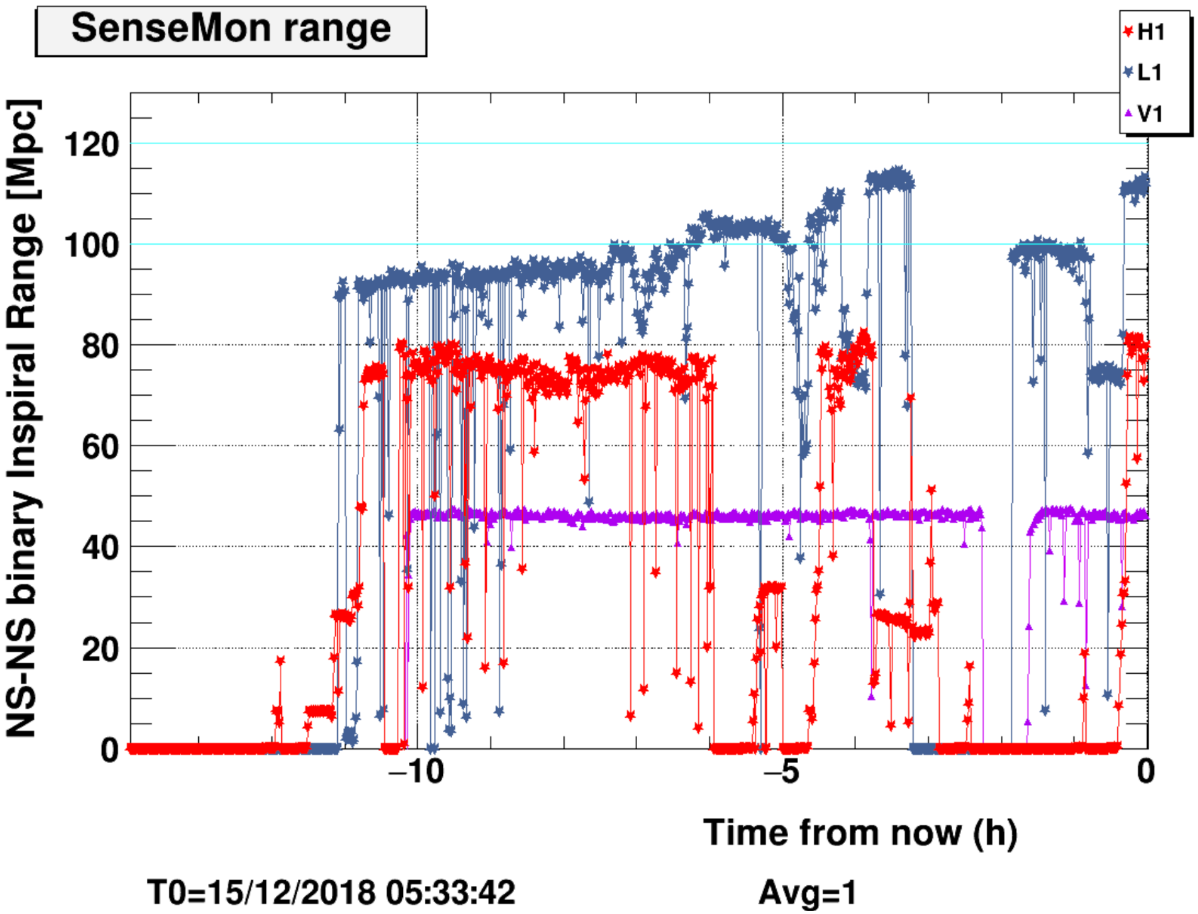
- During O2, low frequency sensitivity limited by thermal noise of metal wires
- Fiber breaking finally understood: contamination of vacuum system by tiny particles from pumps, which were blasting the fibers during a vent
- Tubing of venting system was changed, added screens and fiber guards, then finally suspended mirrors with monolithic fibers again
- Sensitivity improved at low frequencies as expected

1/f^2 noise



- Got stuck for a few months due to low-frequency noise with 1/f^2 frequency dependency, down to 20 Mpc from 30 Mpc
- Big campaign to find origin: finally understood culprit to be a static electrical charge on the mirrors, combined with common mode noise of new electronics: spurious electrostatic actuation (nominal actuation uses voice coils)
- Straightforward fix of electronics once understood

Engineering Run 13 (ER13)



LIGO Livingston

LIGO Hanford

Virgo

Gravitational Wave Detector Network

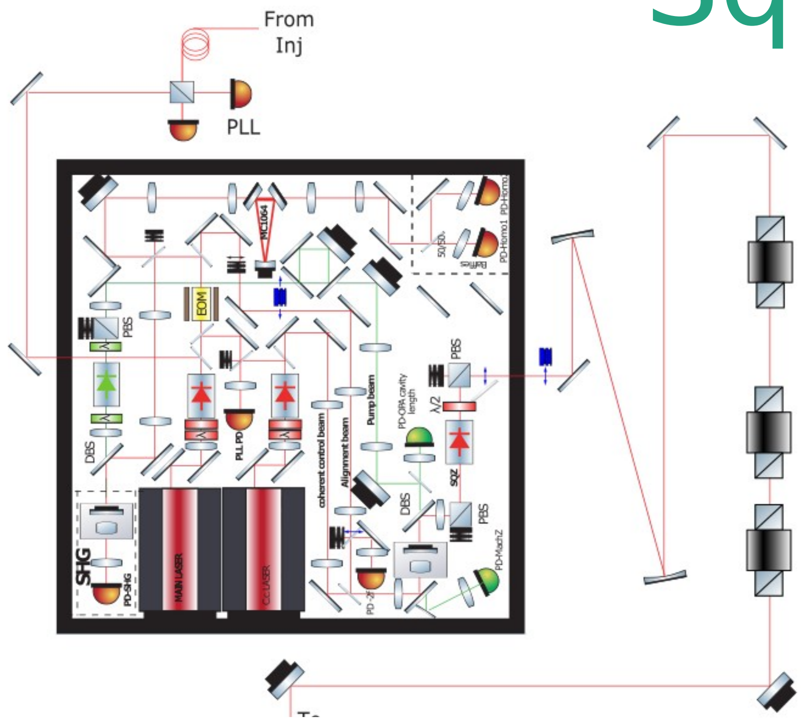
Operational Snapshot as of Dec 16, 05:34 UTC

Detector	Status	Duration
GEO 600	Observing	1:24
LIGO Hanford	Observing	0:12
LIGO Livingston	Observing	0:06
Virgo	Science	1:33
KAGRA	Future addition	

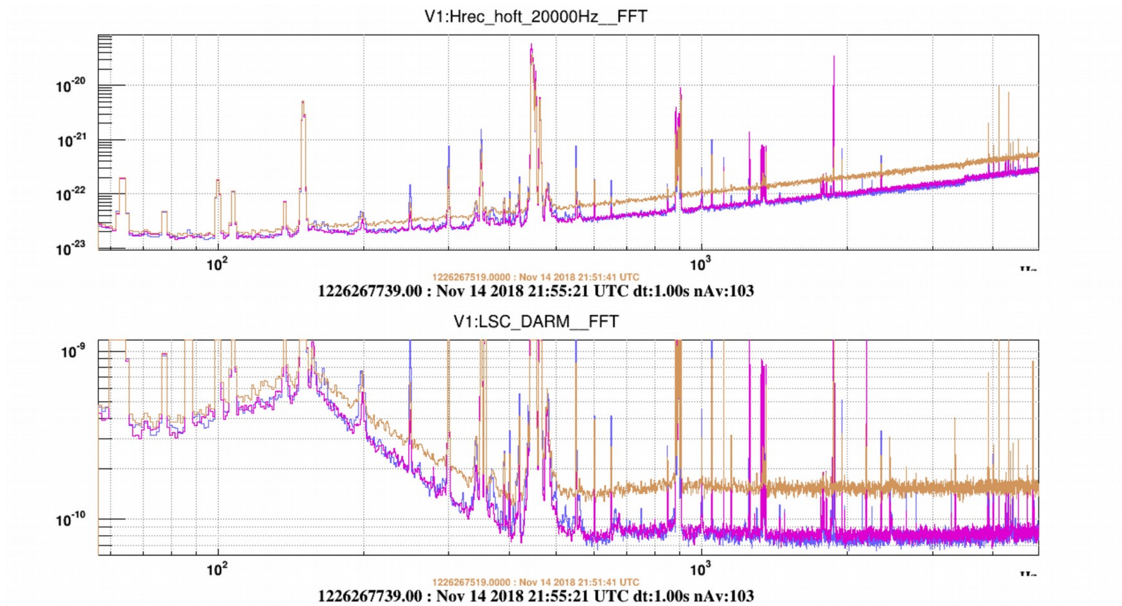
Detector status summary pages   LVC links

- 4 day engineering run ending today, good test for software pipelines, rapid alerts, detector characterization
- Virgo stable around 45 Mpc

Frequency Independent Squeezing

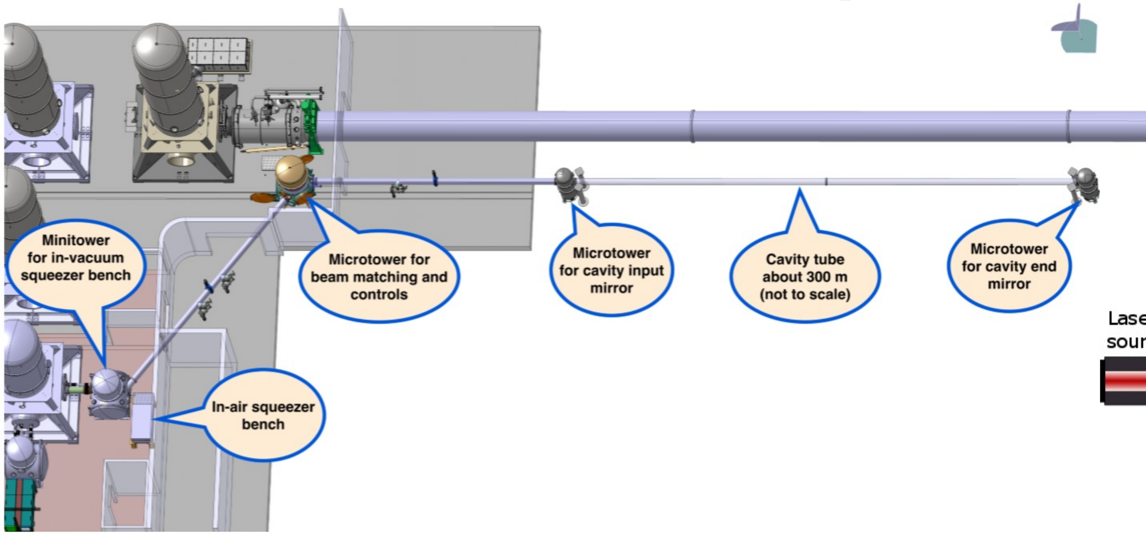


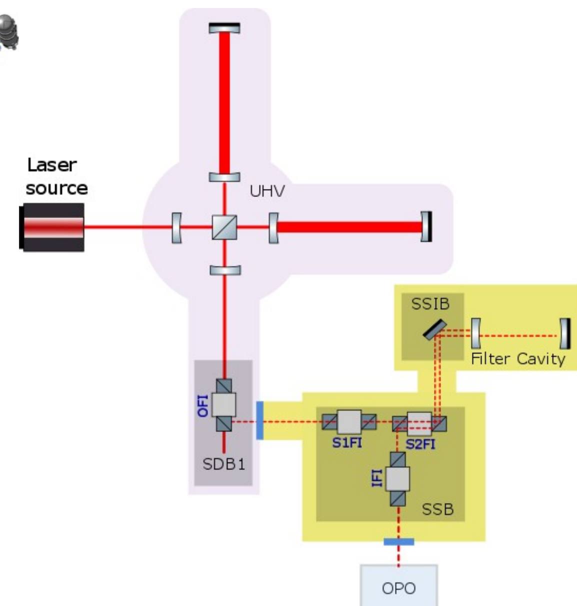
to interferometer

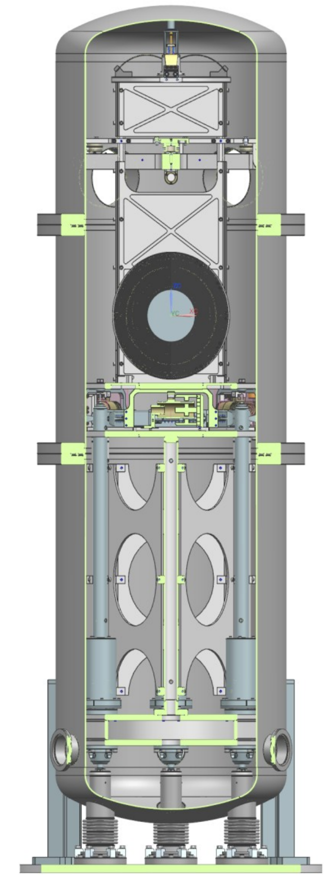


- Sensitivity limited by quantum effects: at low frequencies radiation pressure of individual photons is kicking the mirrors, shot noise at high frequencies causes phase fluctuations in interferometric readout
- Increasing laser power improves high frequencies, worsens low frequencies
- Similar improvements obtained by injecting a squeezed vacuum state back into the interferometer
- Being commissioned right now, so far 5.9 dB of anti-squeezing, <0.5 dB of squeezing

Frequency Dependent Squeezing







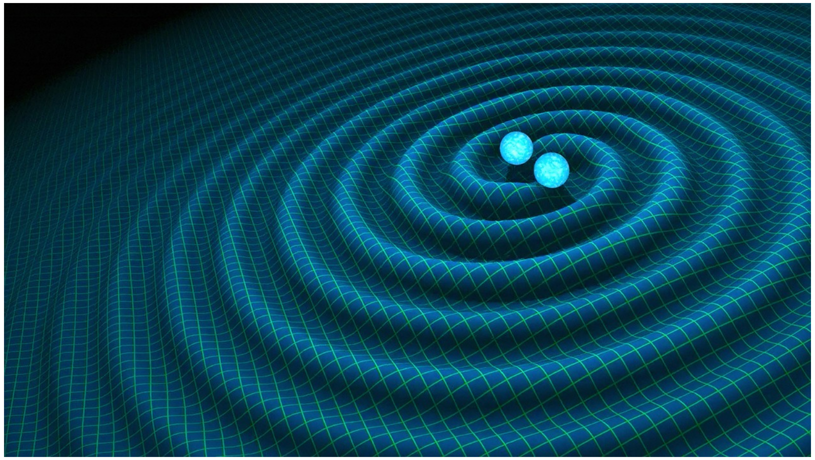
- Get the best of both worlds by ‘rotating the squeezing ellipse’ at intermediate frequencies, needs a ~300 m filter cavity
- Main part of upgrade funded by NWO Groot grant, Nikhef is leading this effort
- Will be installed in ~1.5 years, after the O3 science run

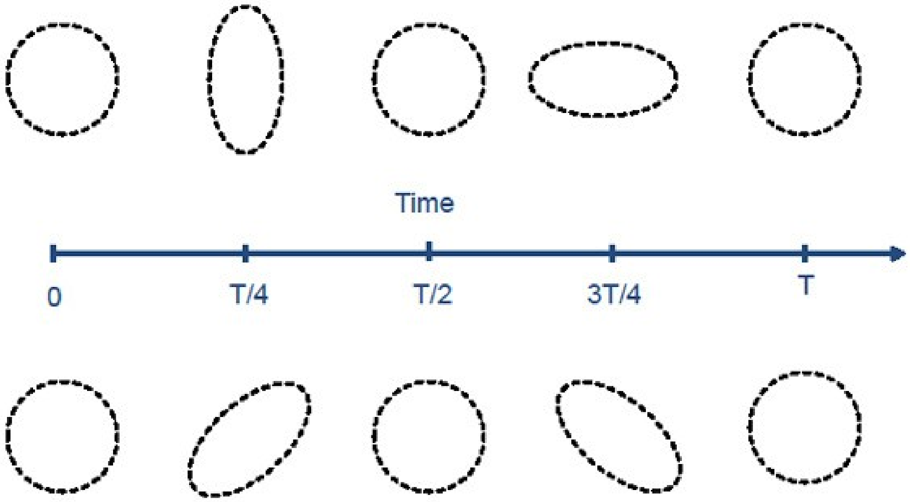
Conclusions

- Significant improvement of Virgo’s sensitivity compared to O2:
  - mirror suspension changed from metal wires to monolithic glass fibers
  - increased laser power
  - frequency independent squeezing (in progress)
  - **enough time for commissioning**
- Almost ready to start the O3 run in ~March 2019
- Best range for Virgo 48 Mpc, LIGO at 90-120 Mpc: detection rate of whole network might be ~1 event/week!
- Before O4: install signal recycling mirror (needs new control scheme), frequency dependent squeezing
- After O4: install bigger mirrors
- Expect a lot of interesting new science in the next years!


End

What are Gravitational Waves?





- 'Ripples in the fabric of space-time' that propagate with the speed of light
- Natural solution to Einstein's equations for General Relativity
- A GW stretches and squeezes space-time in transverse direction, 2 possible polarizations
- Gravitational wave strain: $h = \frac{\delta l}{l}$
- Generated when masses are accelerated (need change of quadrupole moment)
- Extremely weak, $h = 10^{-21}$ for typical astronomical sources

International network

2x LIGO USA	INDIGO India	Virgo, Italy	GEO, Germany	KAGRA, Japan	LISA, space
4 km	4 km	3 km	600 m	3 km, cryog., underground	10^6 km
Operational 2015	Planned 2022	Operational 2017	Operational	Planned 2020	Planned 2034