La deuxième génération des détecteurs d'ondes gravitationnelles

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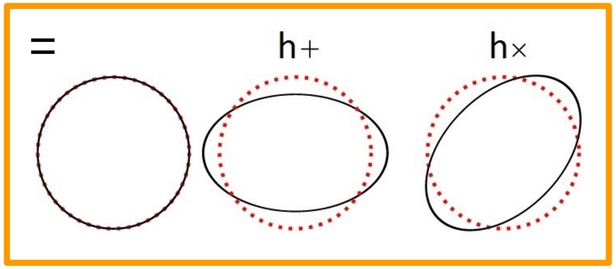
GW detection principle

- **Effect** on Earth of the passage of a GW → *change on the distance between test masses*

$$\delta L \sim h \cdot L$$

GW amplitude

- **Differential effect:**



Test mass:

mass that senses only the gravitational force

MICHELSON INTERFEROMETER + SUSPENDED MIRRORS

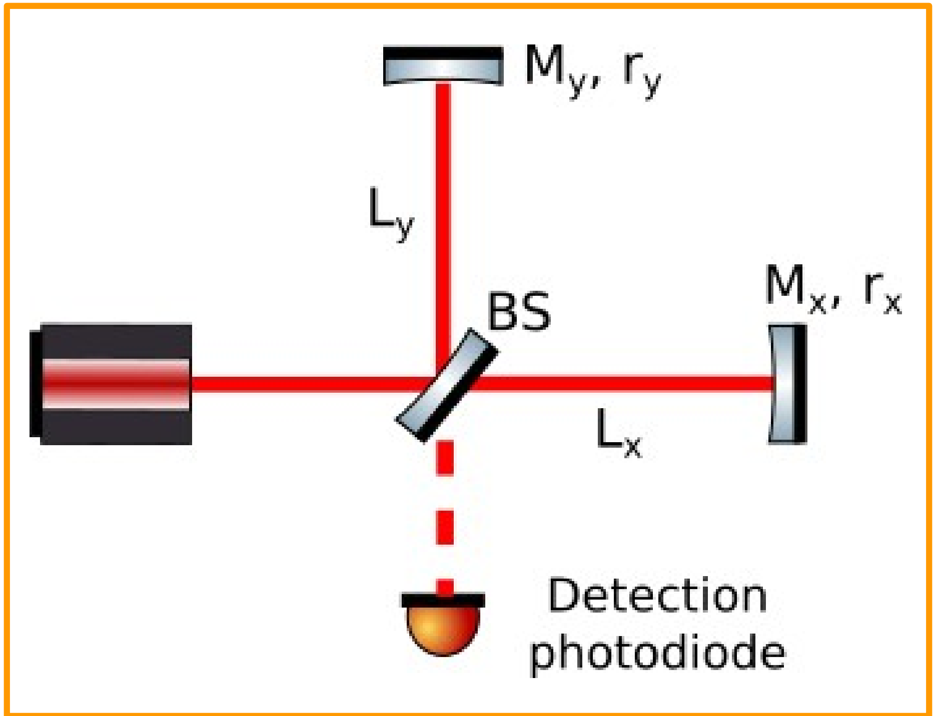
Interference depends on the phase difference between the Michelson arms → *sensitive to length difference*

$$\delta\phi = \frac{2\pi}{\lambda}\delta L$$

GW detector working point

- **GW passage** will cause a $\delta L = L_x - L_y$ → change on the interference condition $\delta\Phi$ → change on the detected power δP_{det}

- **Target:** *maximize the* δP_{det} induced by the passage of the GW → **maximal sensitivity**
  - Limited by the ***shot noise***



Working point: Michelson in **Dark Fringe**

(No light goes to the photodiode, all goes back to the laser)

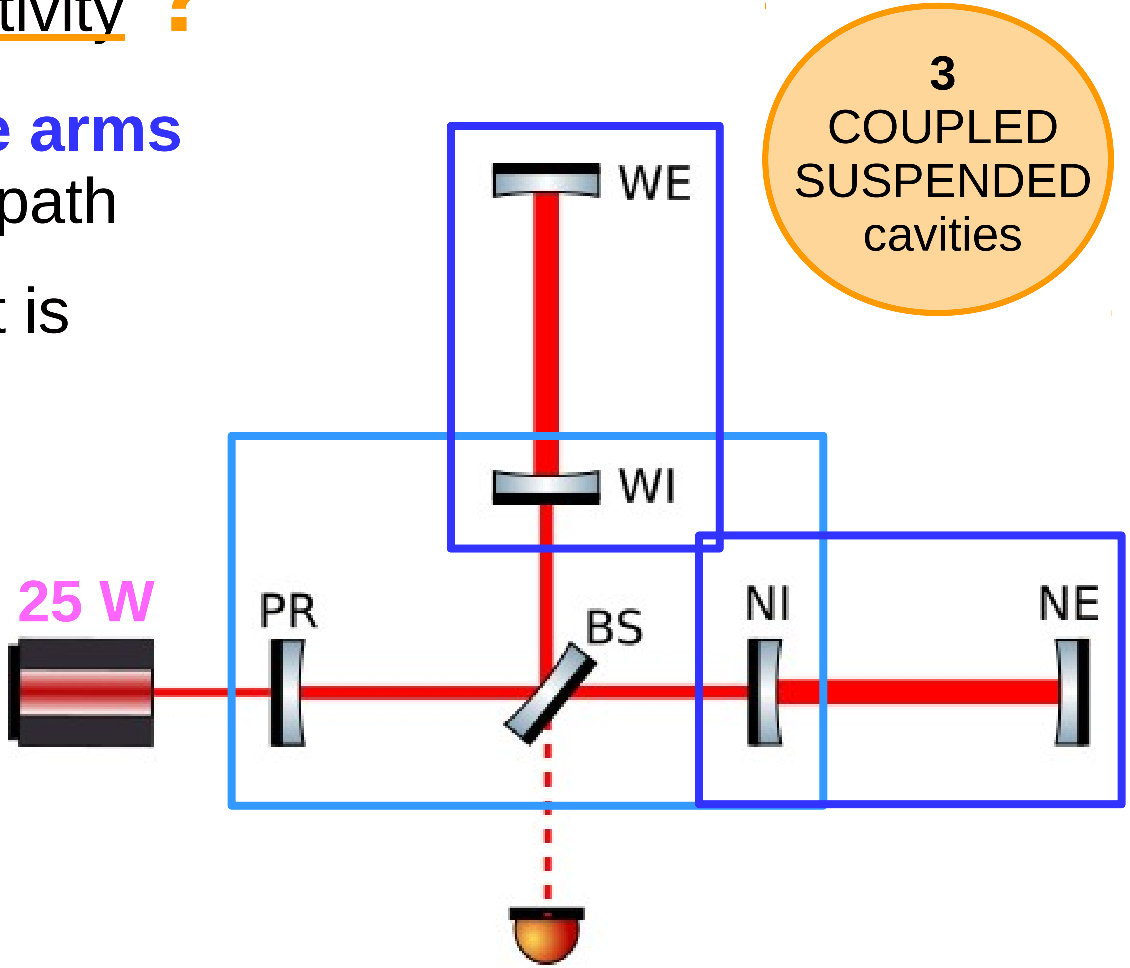
Simple Michelson not enough sensitivity → **NEED h ~ 10^{-19}!**

1st generation of GW detectors

How can we improve the sensitivity **?**

1) Fabry-Perot cavities in the arms (3 km) → increase the optical path

- Optical resonators: the light is reflected back and forth
- **Optical gain** of Virgo+ arm cavities ~100 → ~300 km!

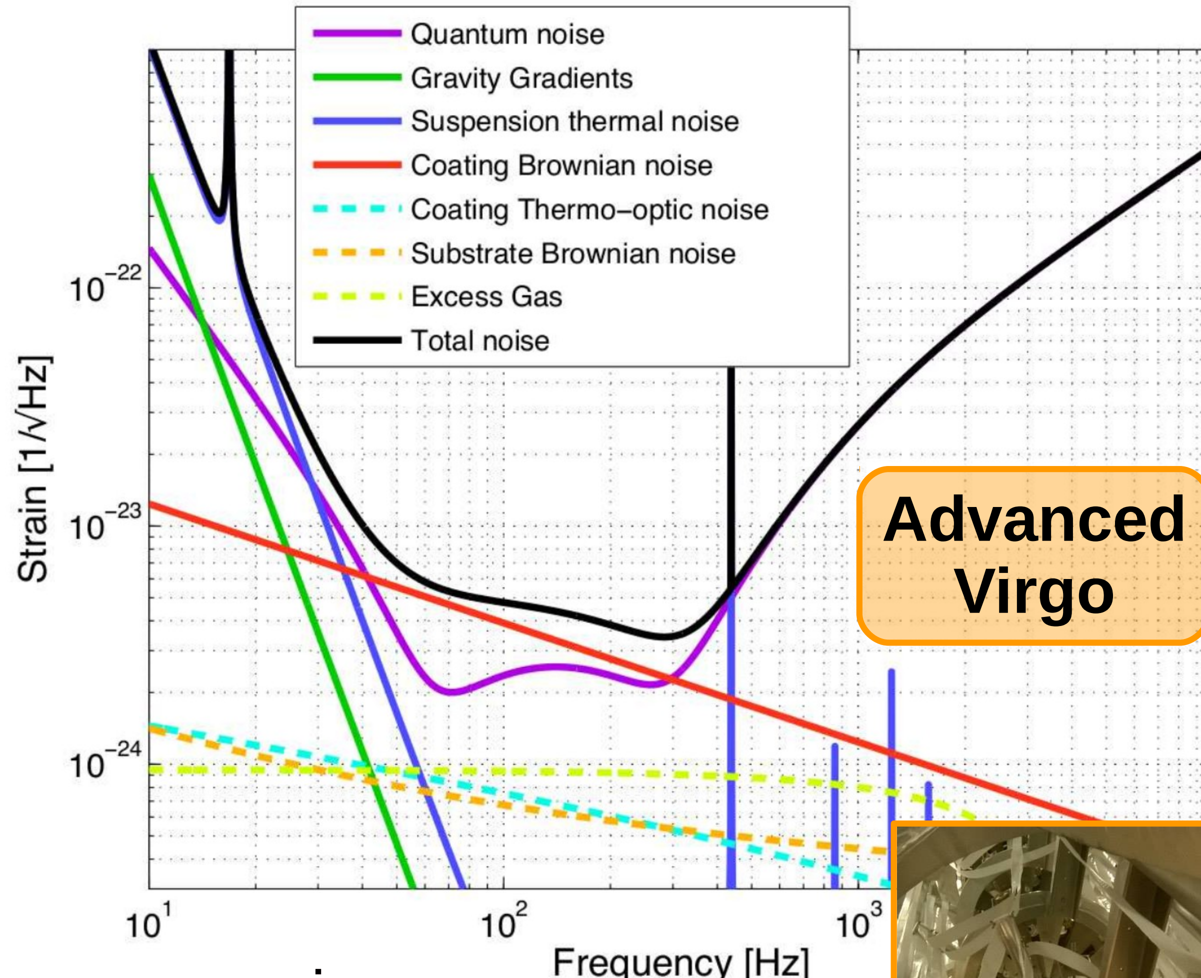


2) Power Recycling cavity → increase the circulating power

- Recycles the light reflected back towards the laser
- The sensitivity is improved by $\sqrt{OG_{PRC}}$

Limiting noises

- **Quantum noise:**
  - Shot noise (high frequency)
  - Radiation pressure (low frequency): force exerted by the photons on the test masses

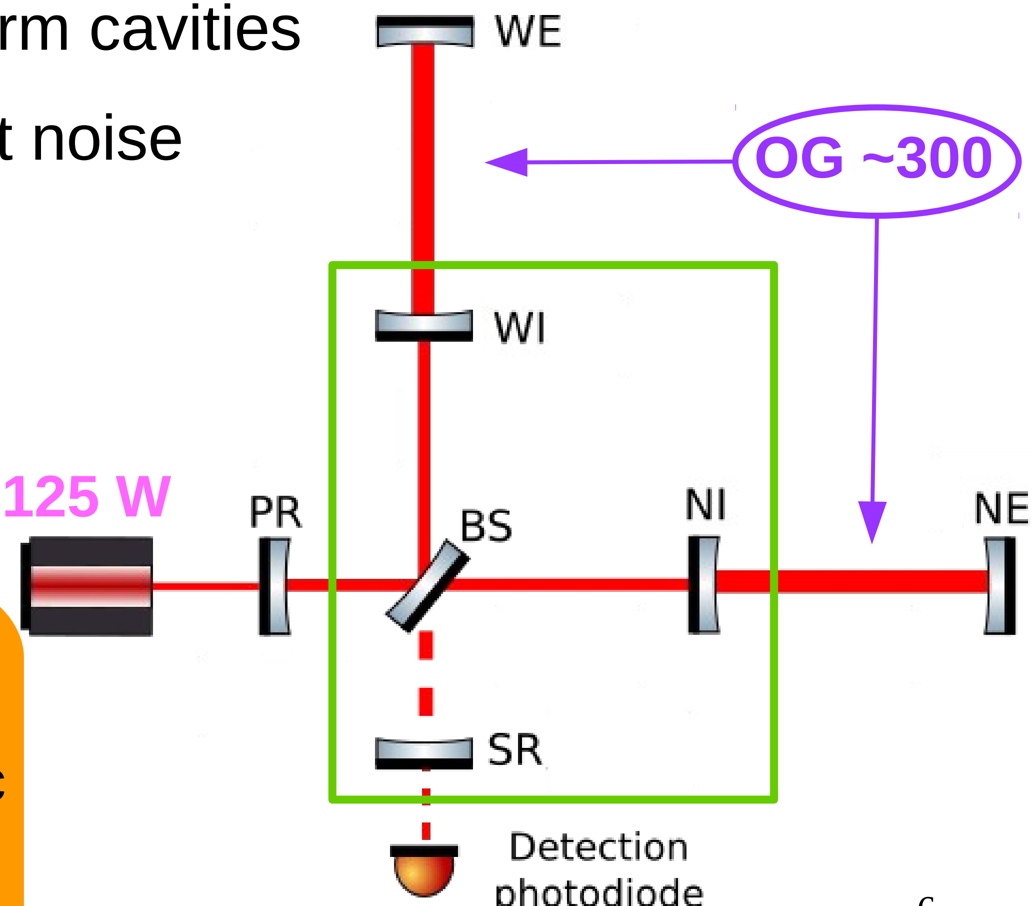


- **Thermal noise:** coating + suspensions
  - Brownian motion due to operation at ambient temperature
- **Seismic noise:** Suspended optics → passive attenuation
  - *Superattenuator* → attenuation 10^{14} above 10 Hz

2nd generation of GW detectors

Not yet in Virgo!

- ✔ **Signal Recycling Cavity:** Recycle the GW signal → Additional mirrror
- ✔ **High power laser:** Increase the input power ← **Not yet implemented!**
- ✔ **Increase optical gain** of the arm cavities
- ✔ **DC readout:** decrease readout noise
- □ **Reduce thermal noise:**
  - *Monolithic* suspensions
  - Increase the *mirror masses*



Advanced LIGO: commissioned between 2010-2015

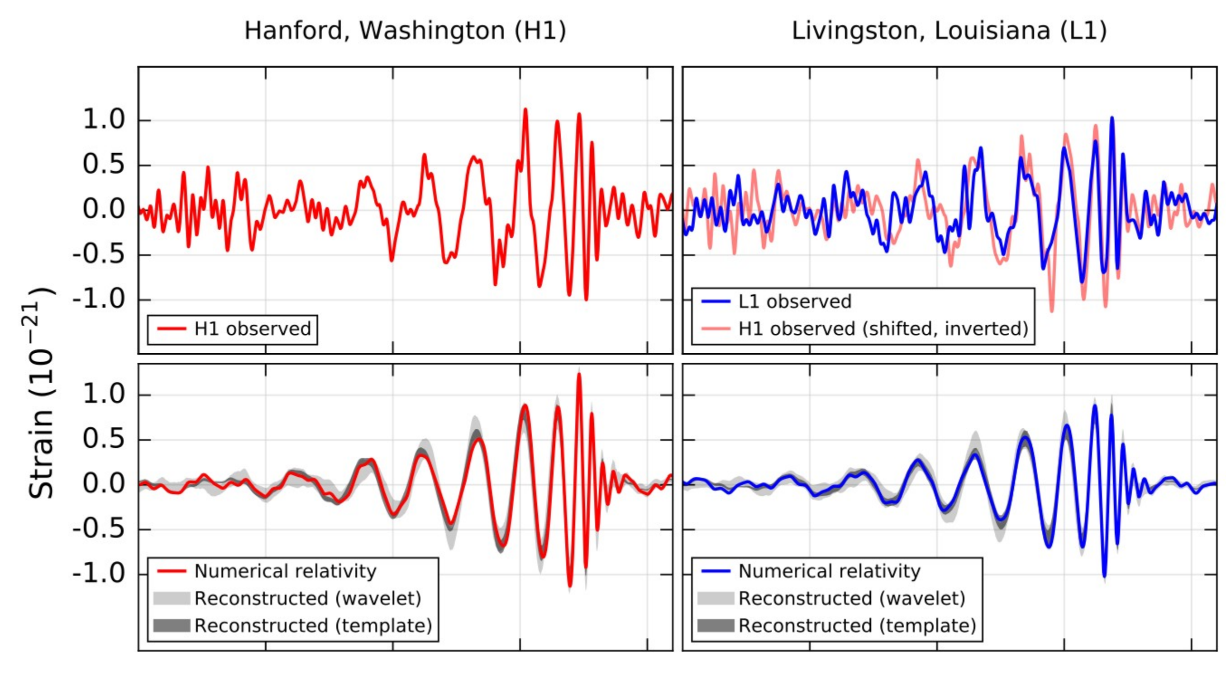
- First scientific run → O1 @ 70 Mpc
- O2 started on November 2016 @ 80 Mpc → until end of August

First detection: GW150914

The 14th of September 2015 the Advanced LIGO detectors in Hanford and Livingston made the first detection of a GW

GW150914:

- *Binary Black Hole*
- Distance: 230-570 Mpc
- Initial masses: ~30 $M_\odot$



GW151226:

- *Binary Black Hole*
- Distance: 250-620 Mpc
- Initial masses: 11-23 and 5-10 $M_\odot$

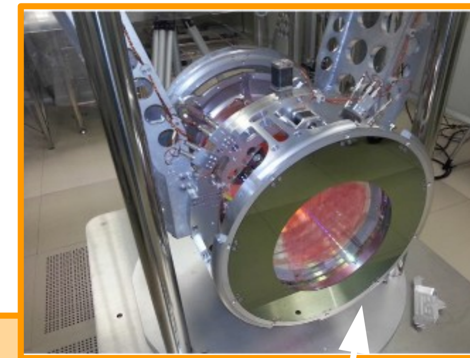
GW170104:

- *Binary Black Hole*
- Distance: 490-1318 Mpc
- Initial masses: 25-40 and 13-25 $M_\odot$

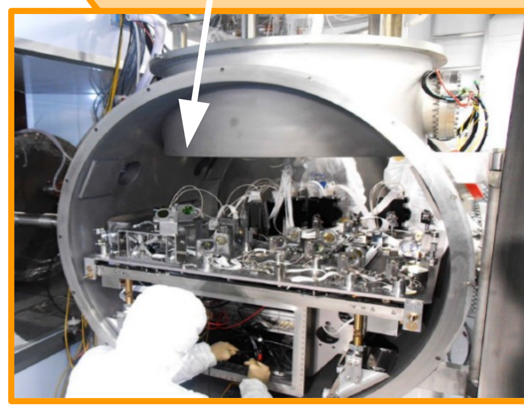
2nd generation: Advanced Virgo

- **Reduce coating thermal noises**
  - ***Geometry of the arm cavities*** changed → waist in the middle to increase beam size on the mirrors

- **Power Recycling cavity *marginally stable***
  - *Thermal Compensation System* to deal with the PRC stability and with the future High Power Laser
    - ➔ *Ring Heater / Central Heating*



- **Reduce diffused light**
  - Detection benches *suspended* and in *vacuum*
  - New system of *baffles* in strategic places to *absorb diffused light*



Advanced Virgo: commissioning started on May 2016 – up to present

Advanced Virgo commissioning

CHALLENGES:

- **Increase of the OG** of the arm cavities → *dynamical effects*
- **Change of geometry** of the arm cavities → complicates the *alignment*
- **PRC marginally stable** → increase *sensibility to alignment* and interferometer optical defects

TECHNICAL PROBLEMS:

- ✗ **Monolithic suspensions** → they broke 6 times
- ✗ **BS actuation** too weak
- ✗ **BS wedge** wrong direction
- ✗ **PR pre-curved**

SOLUTION

- ✔ Change by *steel wires*
- ✔ Caused by the vacuum pump → to be replaced
- ✔ *Additional magnets* (x6)
- ✔ Adapted the design of the *detection optical bench*

Commissioning status

First step: bring the interferometer to its working point

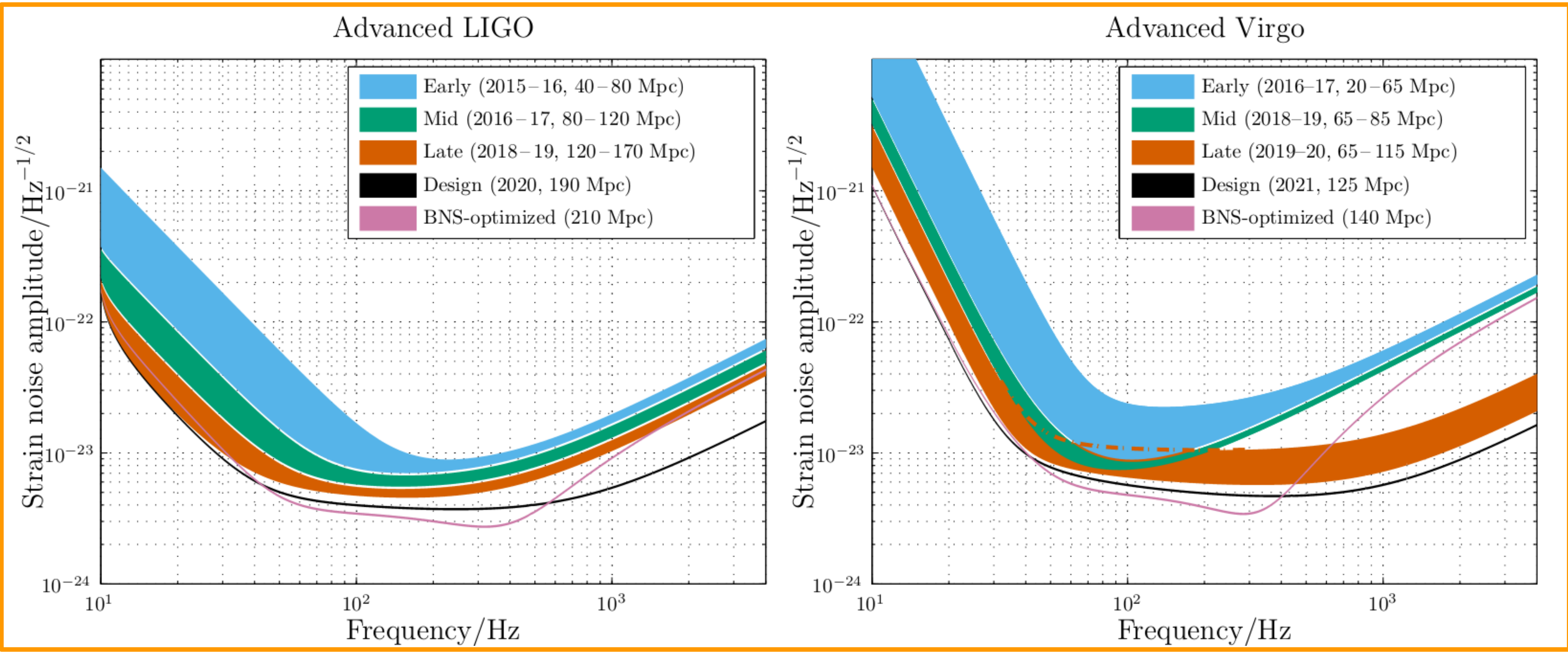
- Longitudinal degrees of freedom (DOFs) are under control
- Basic angular DOFs are controlled → until the TCS is commissioned
- During the first engineering run (5th to 8th of May 2017) the duty cycle was of 85%
- **This part lasted from May 2016 to April 2017**

Second step: reach the best sensitivity possible

- Noise hunting period → identify the limiting noises and supress/mitigate them
- Iterative process → with less noise controls can be fine tuned
- **So far the sensitivity reached is 10 Mpc (BNS horizon)**
- *Target to join O2 is 15 Mpc*

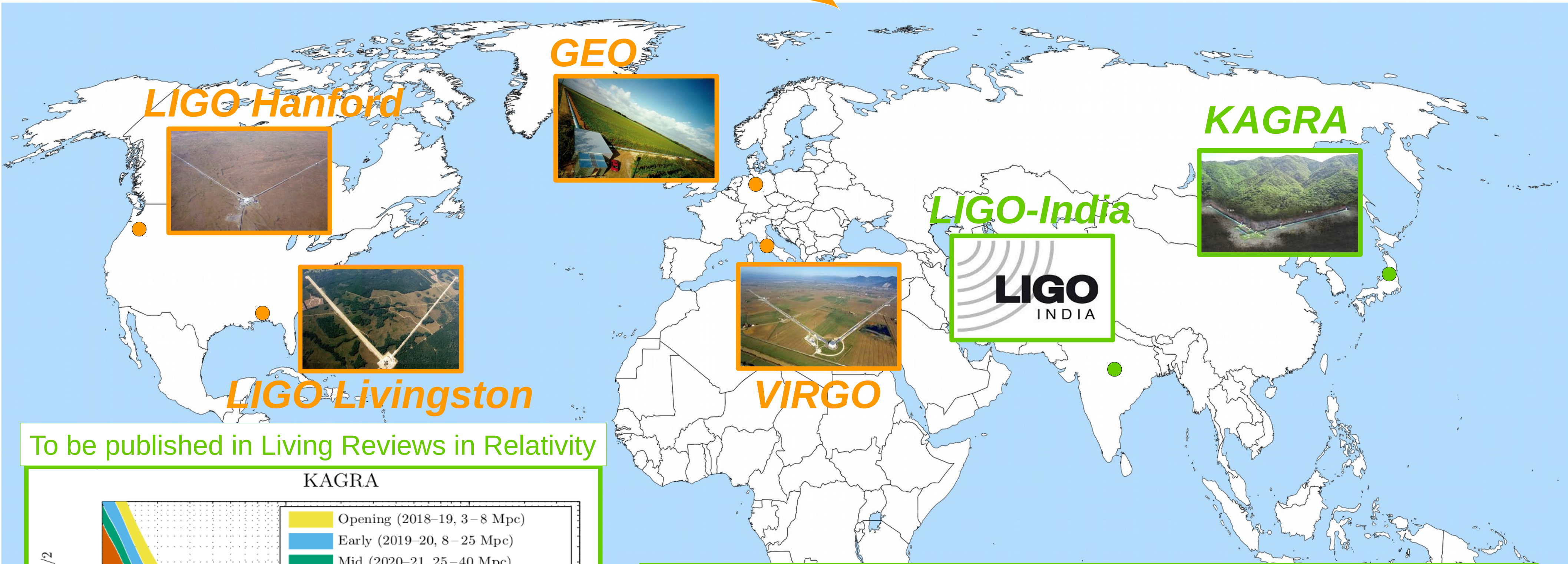
Design sensitivity

To be published in Living Reviews in Relativity, 2017



By **2022 it is foreseen to reach the design sensitivity** (including SR mirror and High power laser) with both Advanced detectors

GW detectors network



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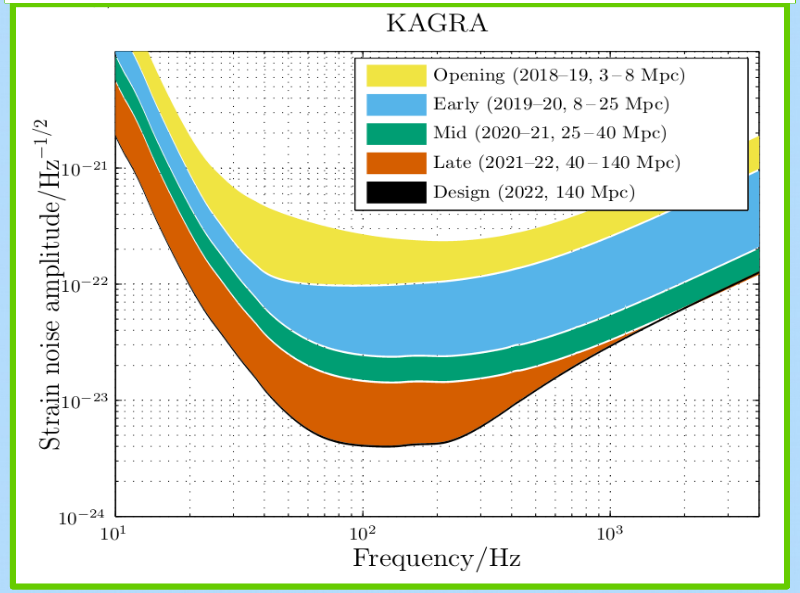


- **KAGRA:** under commissioning → 2019 data taking
  - Underground, cryogenics
- **LIGO-India:** project under development
  - 2023 start commissioning

Future upgrades: Advanced+ detectors

After reaching the design sensitivity, **what is next ?**

- Improve the sensitivity until **limited by the infrastructure**

SQUEEZING:

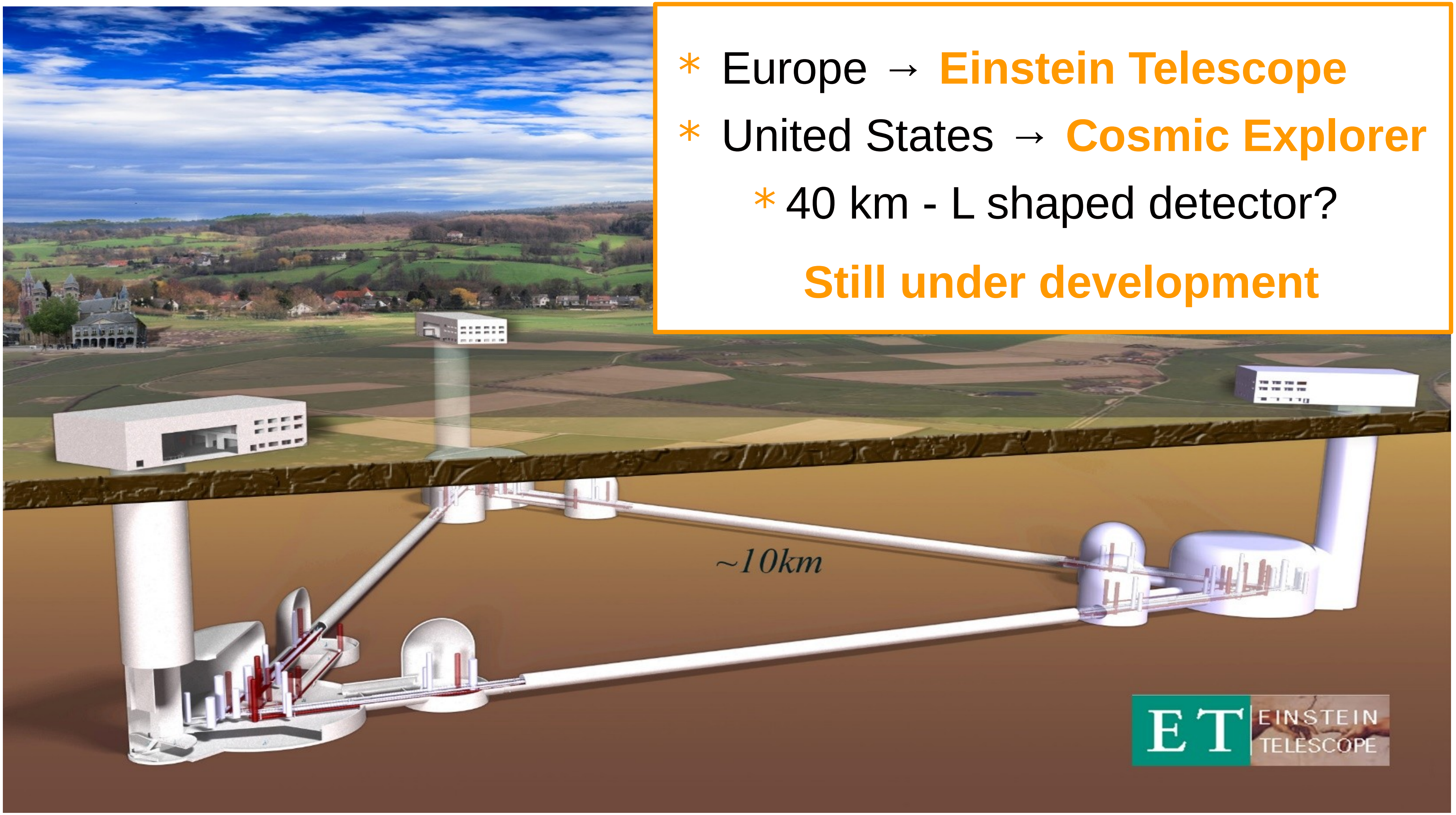
- **Aim:** *reduce the quantum noise* by acting on the two correlated variables of light, **power and phase**
- **Frequency independent**: improves at high frequency and worsens at low frequency or viceversa
- **Frequency dependent**: it allows to optimize at the full bandwidth

NEWTONIAN NOISE:

- **Transients on the local gravitational field** produce Newtonian forces on the test masses → important *below 10 Hz*
- **Active cancellation** is being studied → sensors are a key point

3rd generation of GW detectors

* **Target:** *improve the sensitivity by a factor 10* with respect to the Advanced detectors



* Europe → **Einstein Telescope**
* United States → **Cosmic Explorer**
  * 40 km - L shaped detector?

Still under development

Einstein Telescope

"Known" technology:

- *Underground* → reduce the effect of seismic noise
- *Cryogenics* (10-20 K) → reduce thermal noise
- *Squeezing* → reduce quantum noise
- *Newtonian noise* suppression
- *High power* laser → parametric instabilities ?
- *Thermal Compensation* System

NEW technology:

- Use of *several wavelengths*
- Arms length of *10 km*
- Xylophone design → ITF @ *low frequency* and @ *high frequency*
- *Independence:* Several interferometers to allow localization, polarisation and high duty cycle (to be decided)

NEWS

FIRST TRIPLE LOCK OF LIGO AND VIRGO INTERFEROMETERS

17 June 2017 -- For the first time, all three second generation interferometers---LIGO Hanford, LIGO Livingston, and Virgo---are simultaneously in a locked state. (When an interferometer is "locked" it means that an optical resonance is set up in the arm cavities and is producing a stable interference pattern at the photodetector.) Virgo is joining in an engineering mode, in preparation for the full triple-observing mode planned for later this summer. Congratulations, Virgo!

Image Credit: Virgo Collaboration

THANK YOU