# The gravitational waves detector Advanced Virgo

Original slides courtesy of
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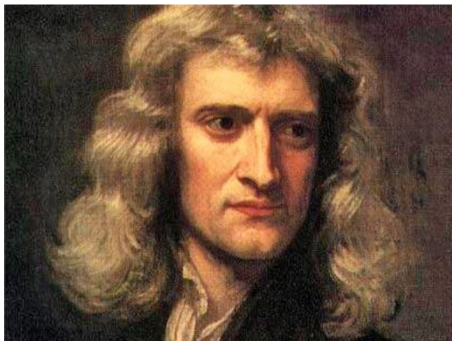
INFN Pisa

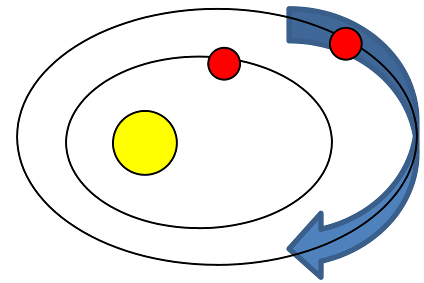
# Introduction

# Gravitational force

## **Newton**, 1687 → Universal gravitation



$$F = G\frac{M \cdot m}{R^2}$$

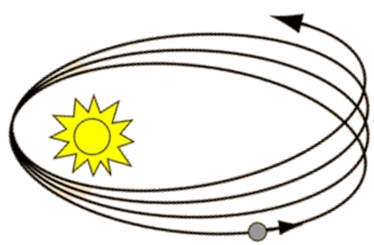


### Pros

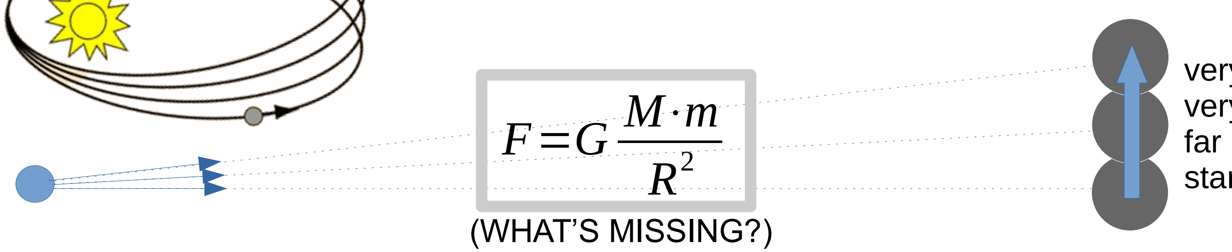
- Very nice correspondence with observations
- One theory for different phenomena
- Dramatic leap of culture and forecasting skills
- Please, stop me

### Cons

- Orbit of Mercury

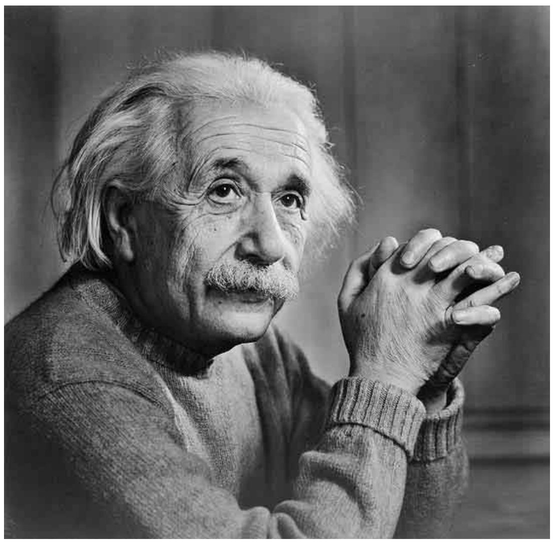


- Try to guess



# Gravitational force

## **Einstein**, 1915 → General Relativity

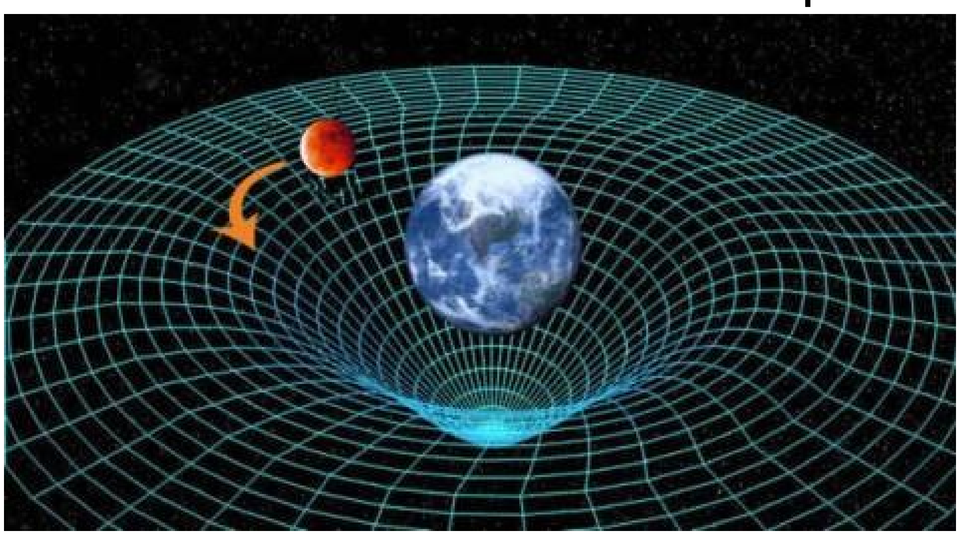


### Some assumptions

- All repetitions of the same experiment in any free falling lab have the same results
- Time and space are deeply involved

### Some consequences

- Gravitation is not an interaction, but a property of space-time

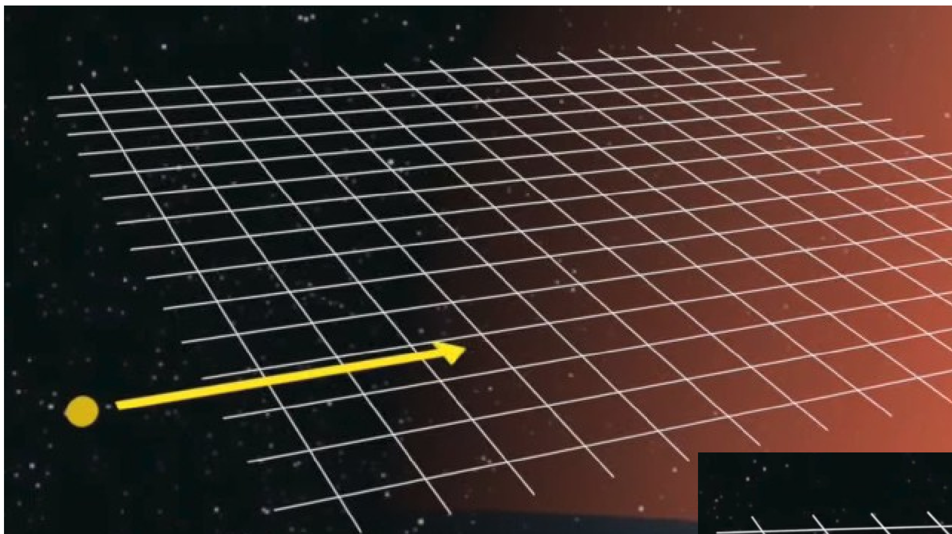


- Mass is the cause (or symptom) of a space-time distortion

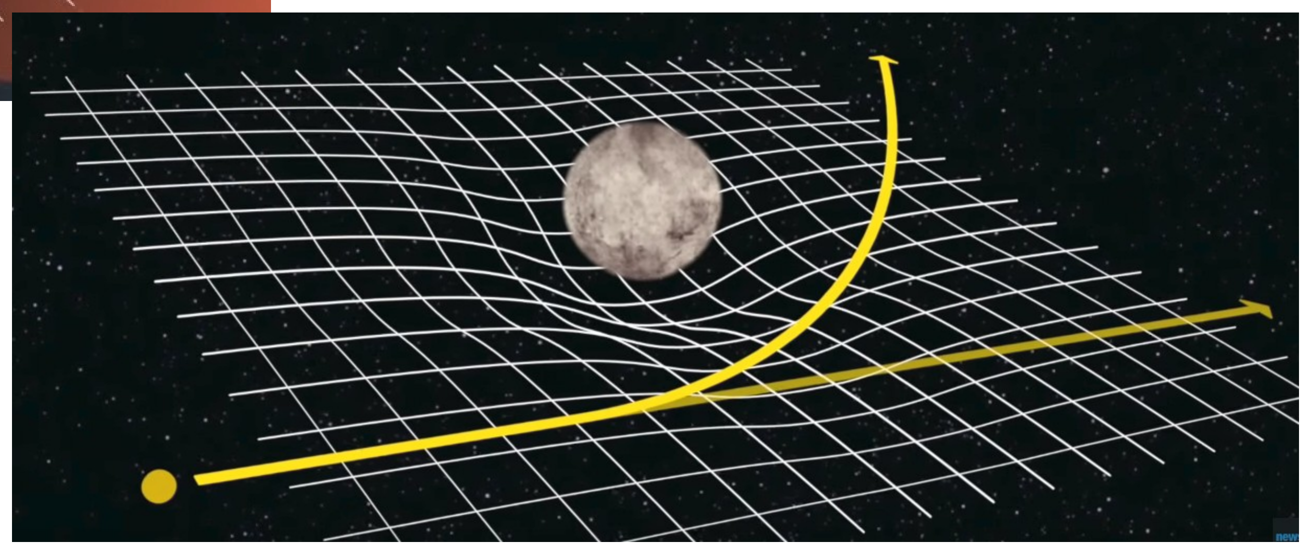
– **Space-time fabric**

# General Relativity

*The presence of objects with mass modifies the space-time curvature*

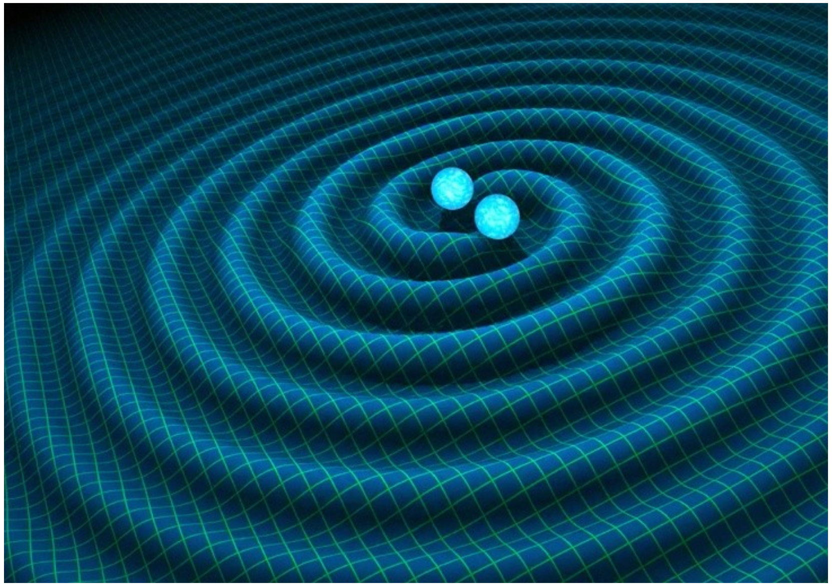


This curvature modifies the trajectory of other objects (and light)

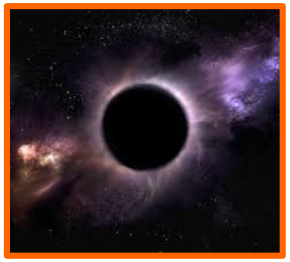


# Gravitational waves

- Predicted by General Relativity
- *Oscillations of the space-time fabric*
- Produced by **big masses** accelerated
  - **Emitted power:** *asymmetric* mass distribution, *compact* and *relativistic.*
  - **Distance:** amplitude decreases as *1/r*

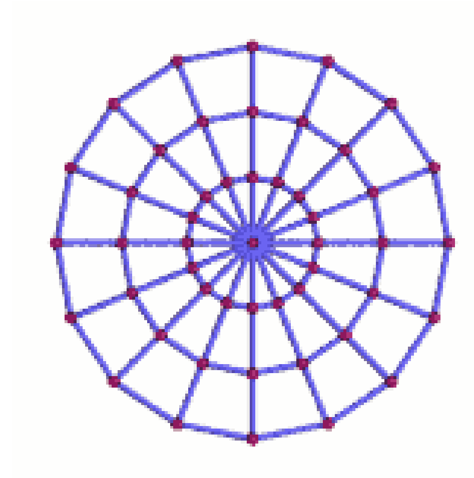


**Black Holes**



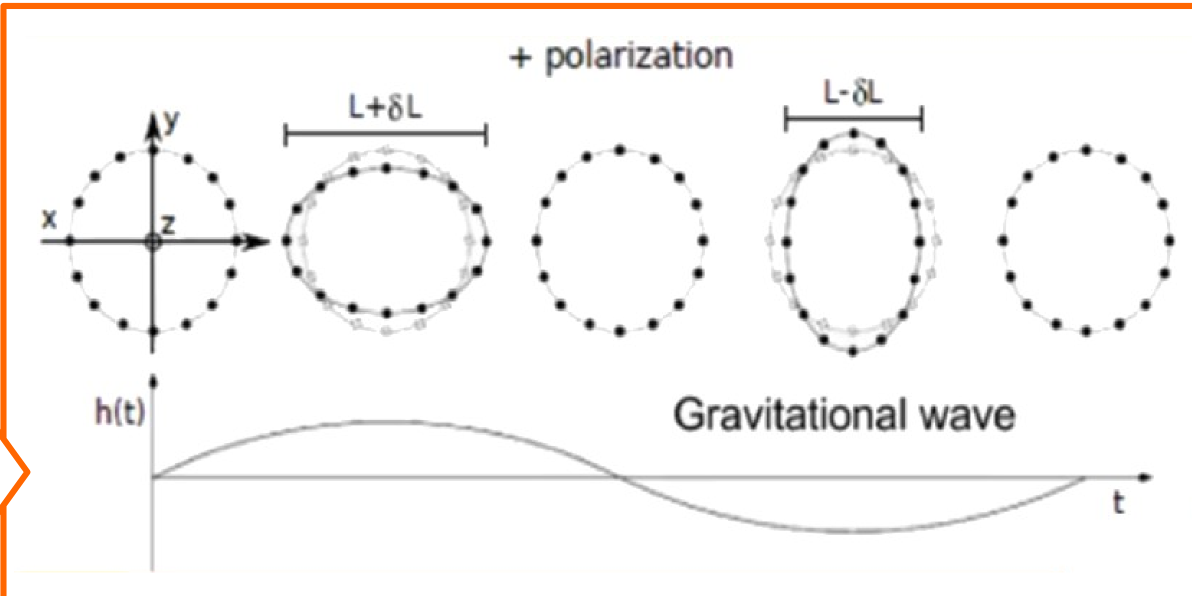
300.000 billions of billions of elephants in a car!

# Characteristics



- They travel at the *speed of light*
- They traverse matter *unchanged*
- How do we notice them?
  - **They distort the space-time fabric** around us → for masses in *free fall*

**Differential effect:**




Animation by Markus Pössel, www.einstein-online.info

# Intensity of expected waves

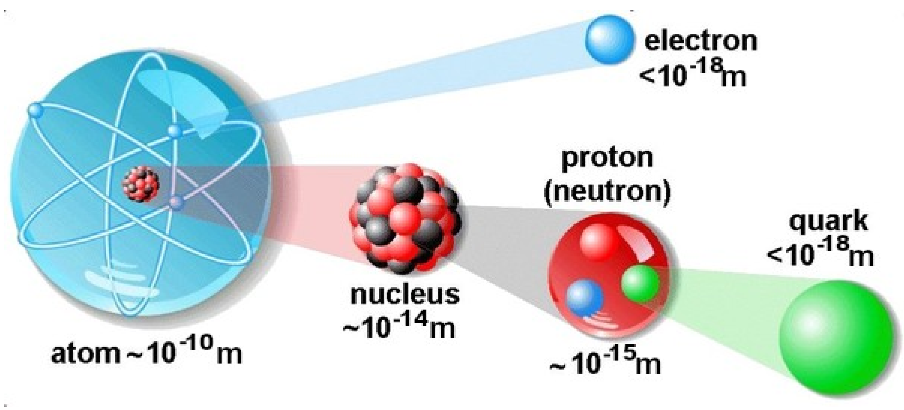
- GW are local *contractions/expansions* of space.

  $$h = \frac{\text{variation of length}}{\text{length}}$$ is a measure of their amplitude

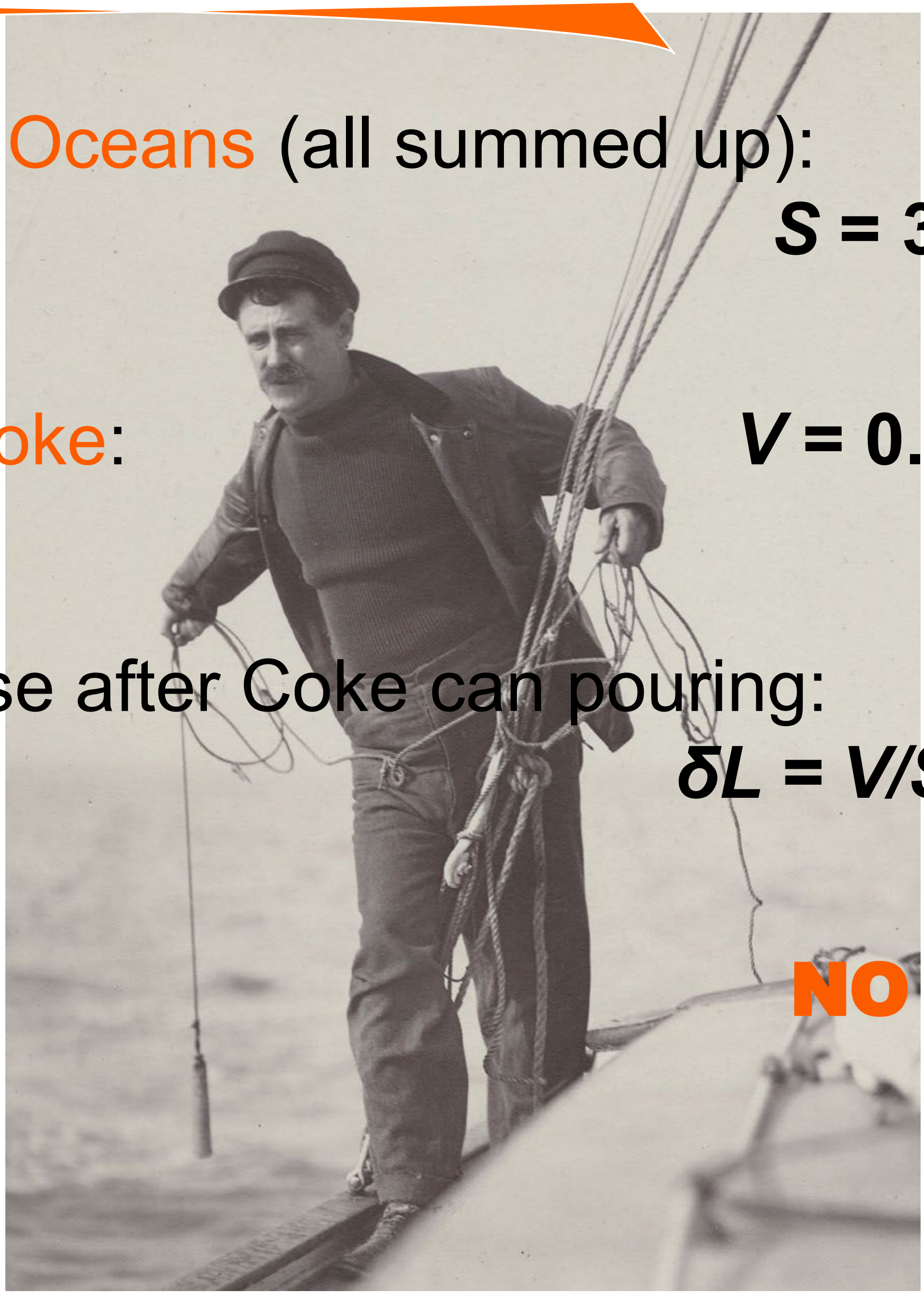
- Far astronomic events →
  $h = 0.000000000000000000001 = 10^{-21}$ on Earth

- With a reference length of 3 km → $\delta L = h \cdot L = 3 \cdot 10^{-18}$ m

**Some interesting lengths in nature:**



# Allegory



- Surface of the Oceans (all summed up):

  $$S = 3.6 \cdot 10^{14}\ m^2$$

- Volume of a Coke:

  $$V = 0.33 \cdot 10^{-3}\ m^3$$

- Ocean level rise after Coke can pouring:

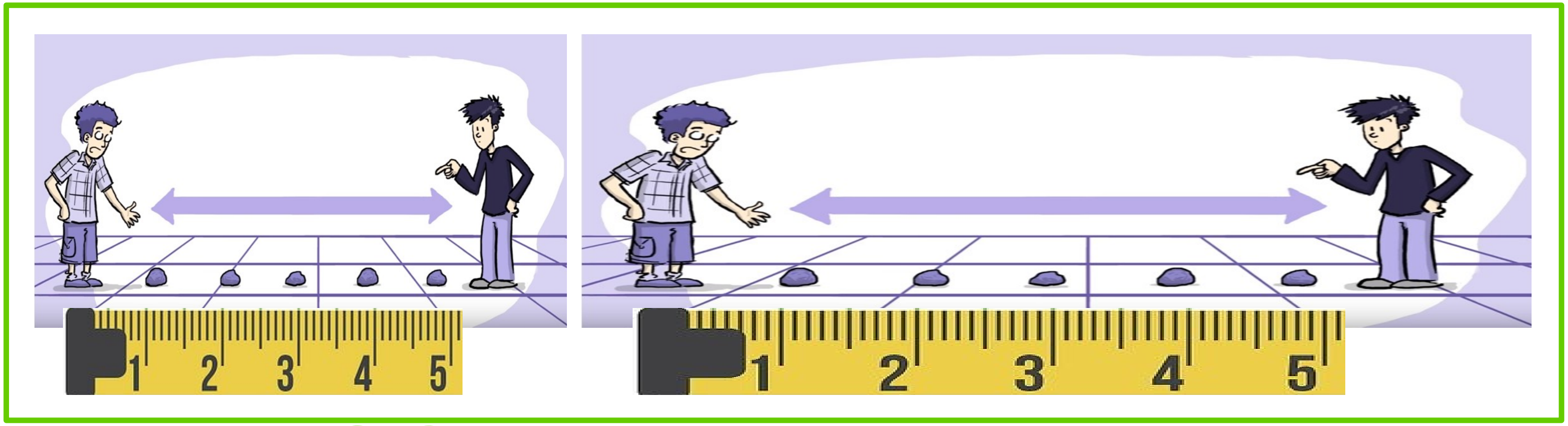
  $$\delta L = V/S = \boxed{10^{-18}\ m}$$

**NO Panic: there are two more Cokes!**

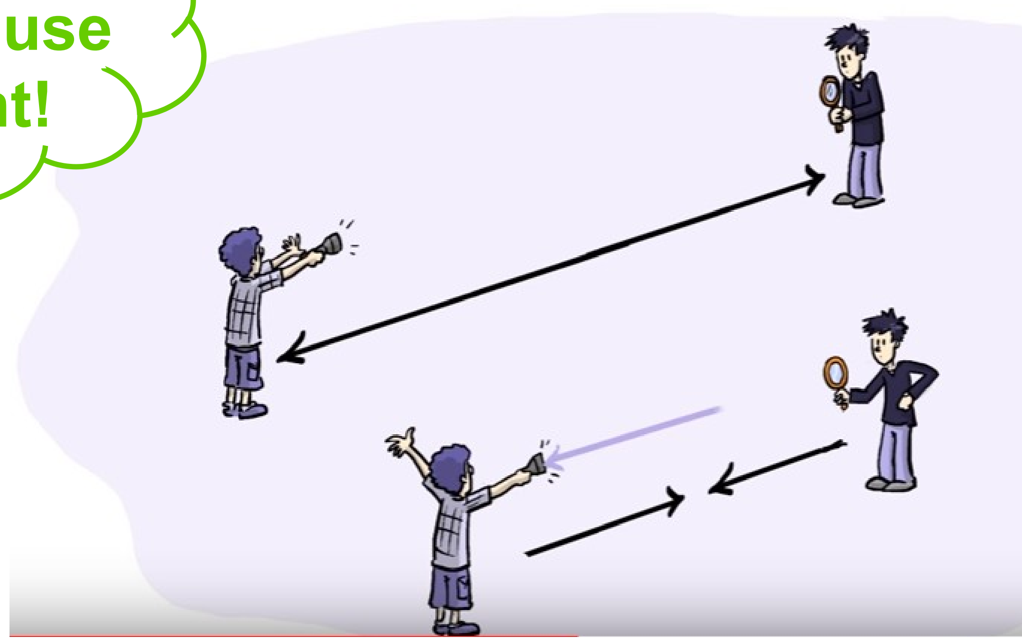
# Detection principle

# How can we detect them?

- We can’t use a meter → it will suffer as well the effects of the GW!







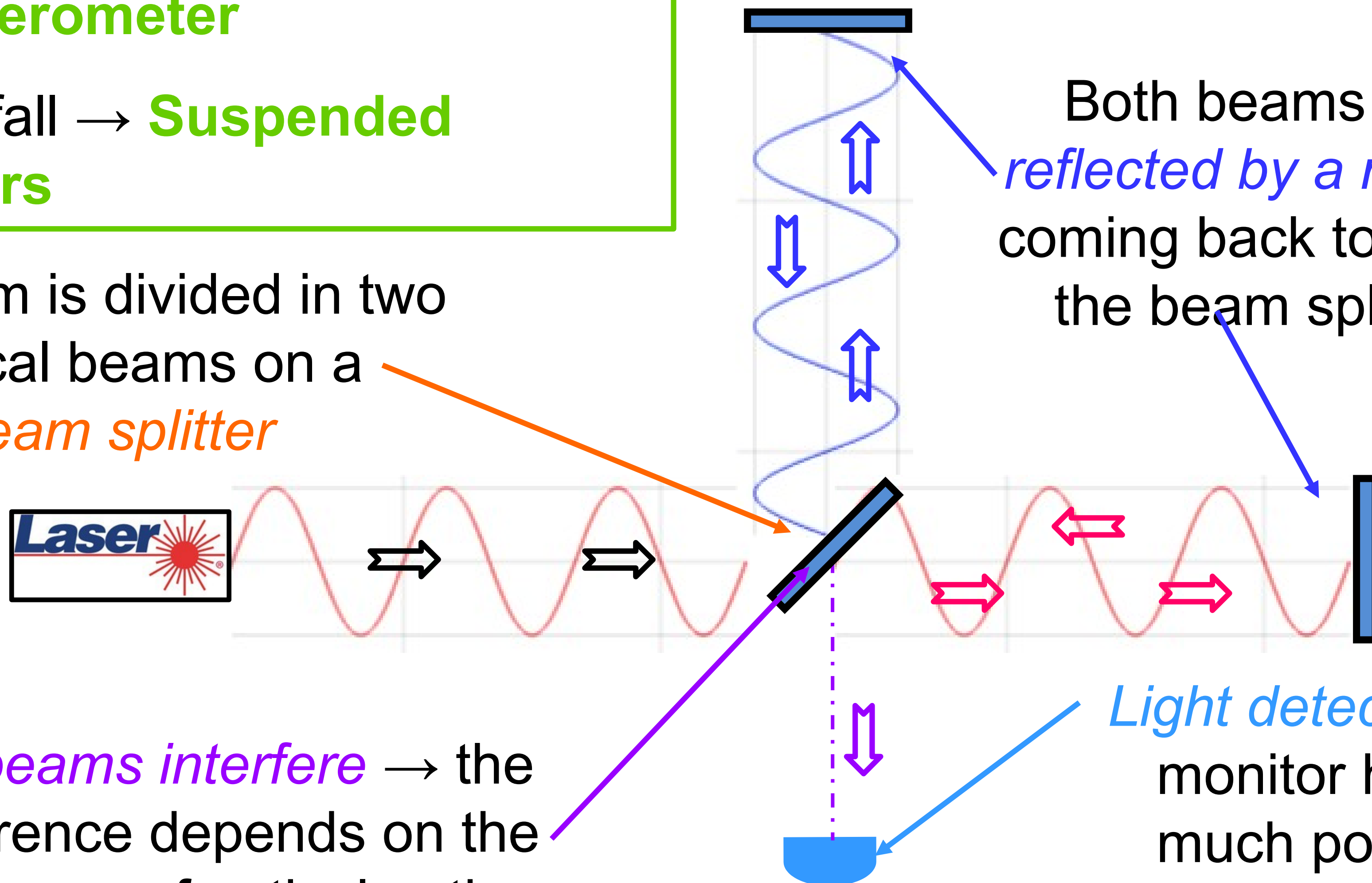
The time that takes light to travel the distance between the two people changes!

# Michelson interferometer

- Differential effect → **Michelson interferometer**
- Free fall → **Suspended mirrors**

The beam is divided in two identical beams on a *beam splitter*

Both beams are *reflected by a mirror*, coming back towards the beam splitter

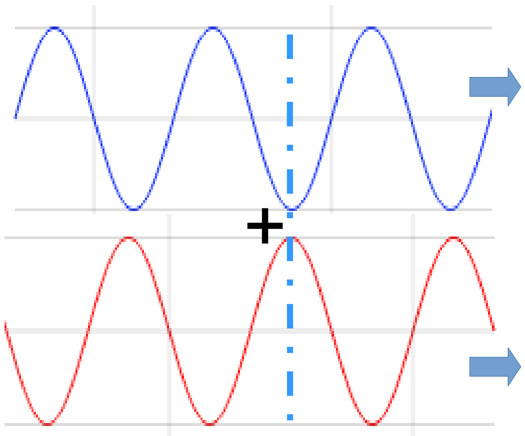



*Both beams interfere* → the interference depends on the <u>difference of optical path traveled</u>

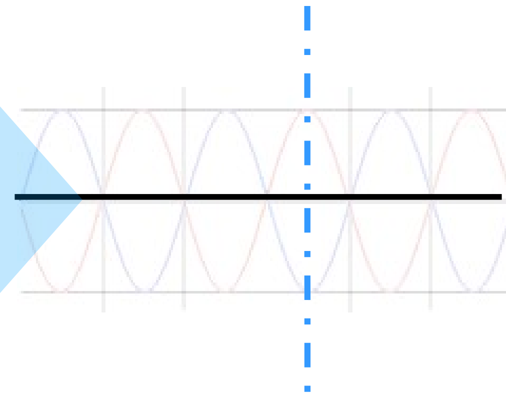
*Light detector* to monitor how much power results from the interference

# Interferences

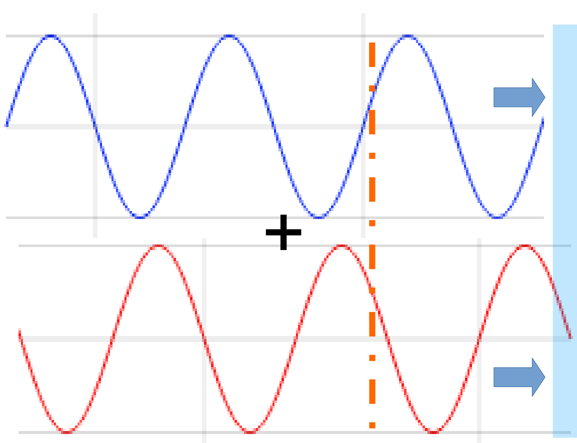
- If both "arms" of the interferometer have **the same length**



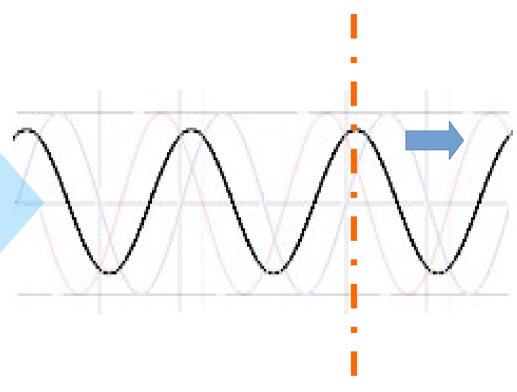
*beams have opposed phase. Thus, when they overlap, they cancel in a perfect way → there is no light reaching the detector*



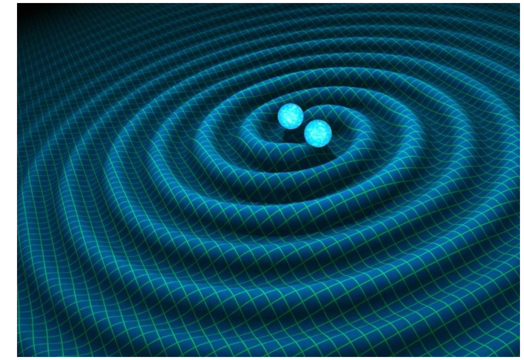
- If there is **one arm longer than the other**



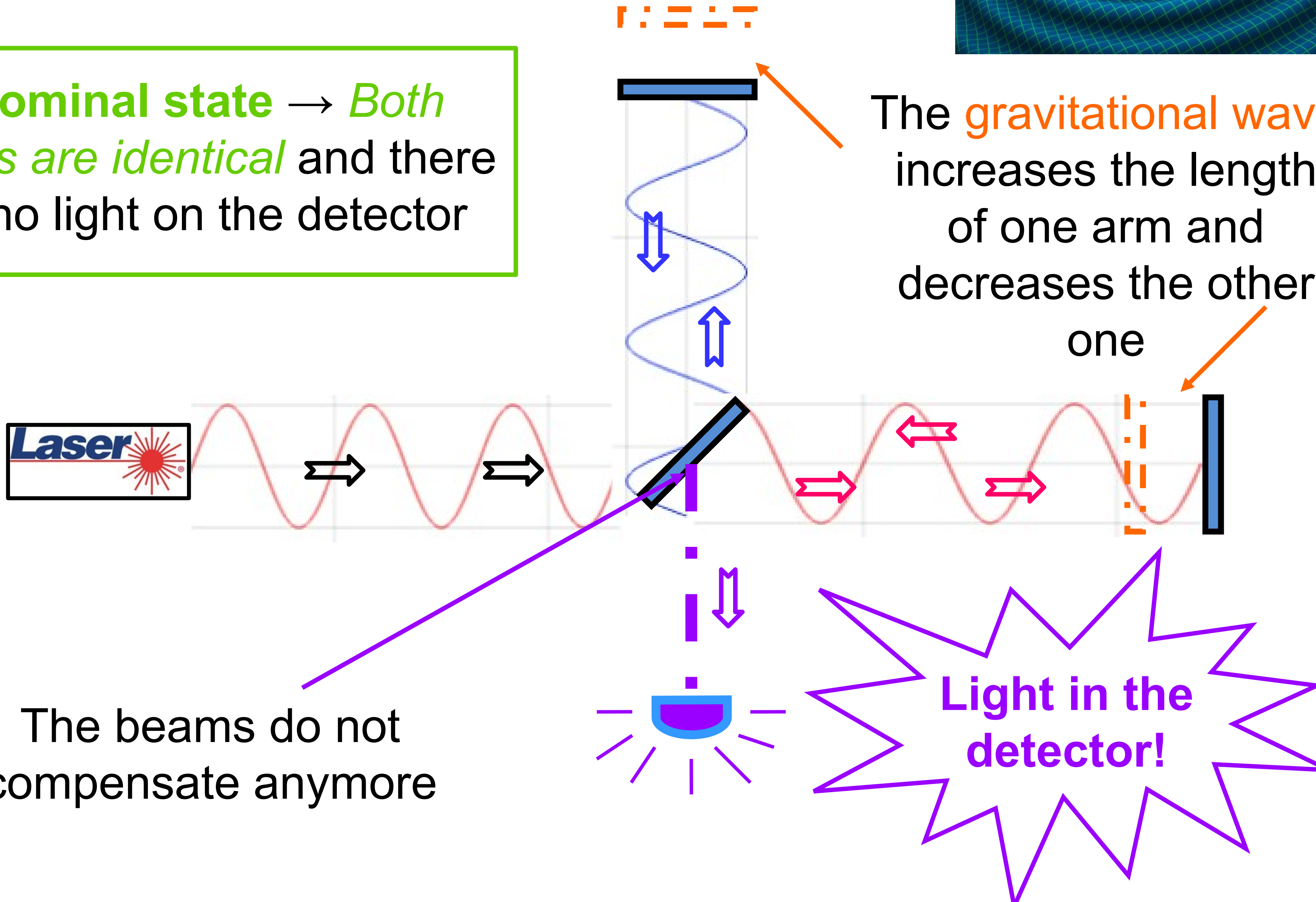
*the sum of the two beams is different from zero → some light reaches the detector*



# Detection principle



**Nominal state** → *Both arms are identical* and there is no light on the detector



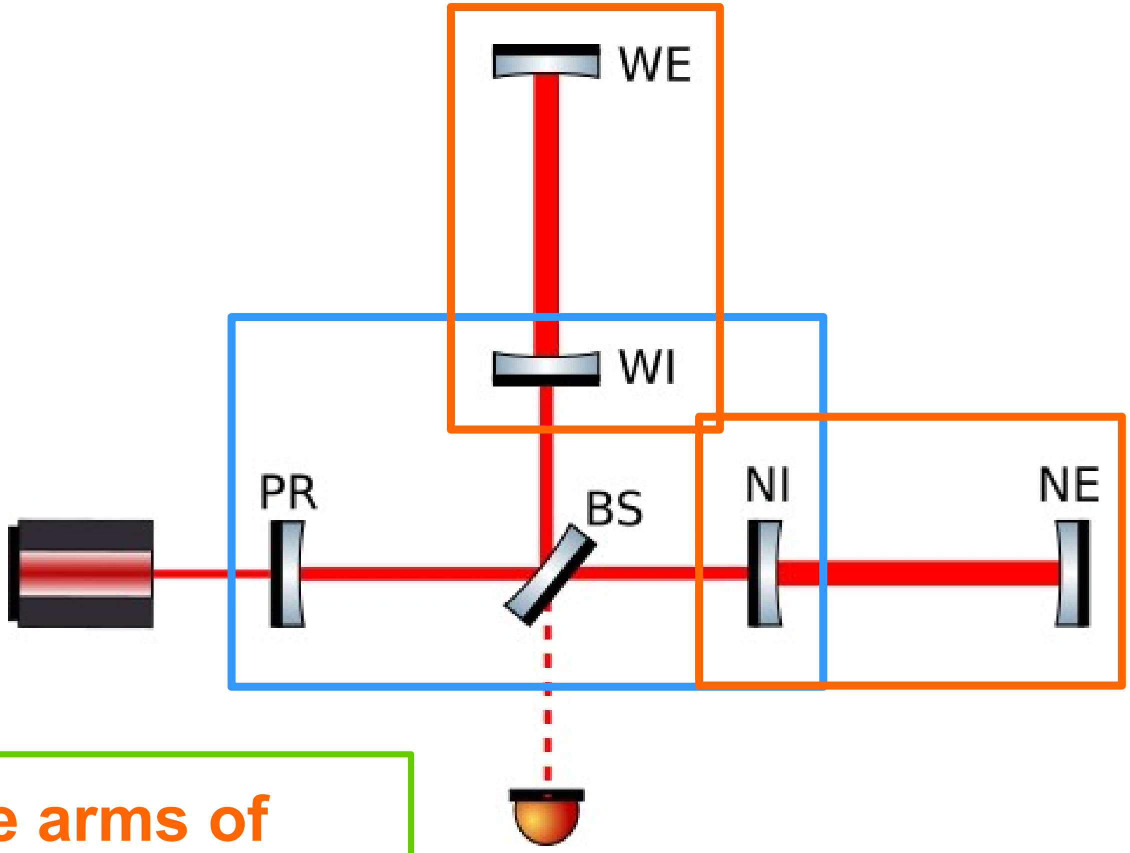

The gravitational wave increases the length of one arm and decreases the other one

The beams do not compensate anymore

# Increase the sensitivity

Table-top Michelson is not sensitive enough → $h_{min} \sim 10^{-17}$

$h_{shot} \propto 1 / (L \cdot \sqrt{P})$




**IMPROVEMENTS:**

1) **Fabry-Perot cavities in the arms of the Michelson (3 km)** → increase the optical path (by a factor ~300)

⚠ 2) **Power Recycling Cavity** → increases the effective input power (by a factor ~30)

3 Optical cavities **suspended and coupled**

# Noise mitigation

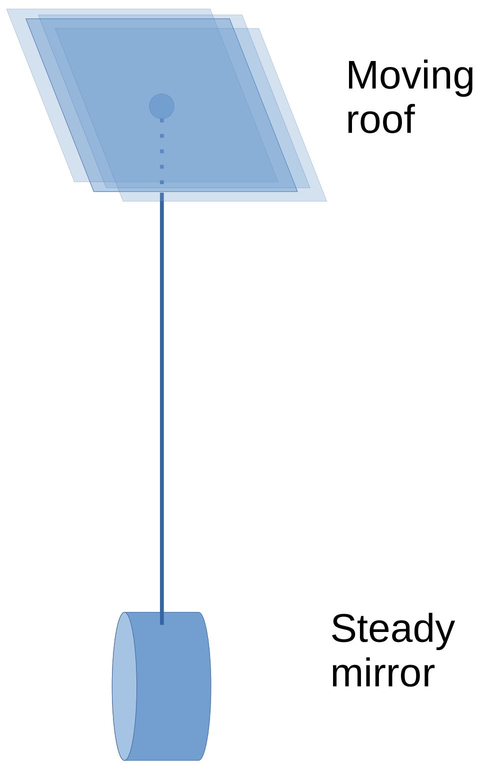
# Noises

- Remember: the required accuracy is **$10^{-18}$ m** out of 3 km → all fluctuations of earth, air, temperature, *etc*, are limiting

- An example: seismic vibrations (RMS amplitude, above 10 Hz): 4 · **$10^{-8}$ m**

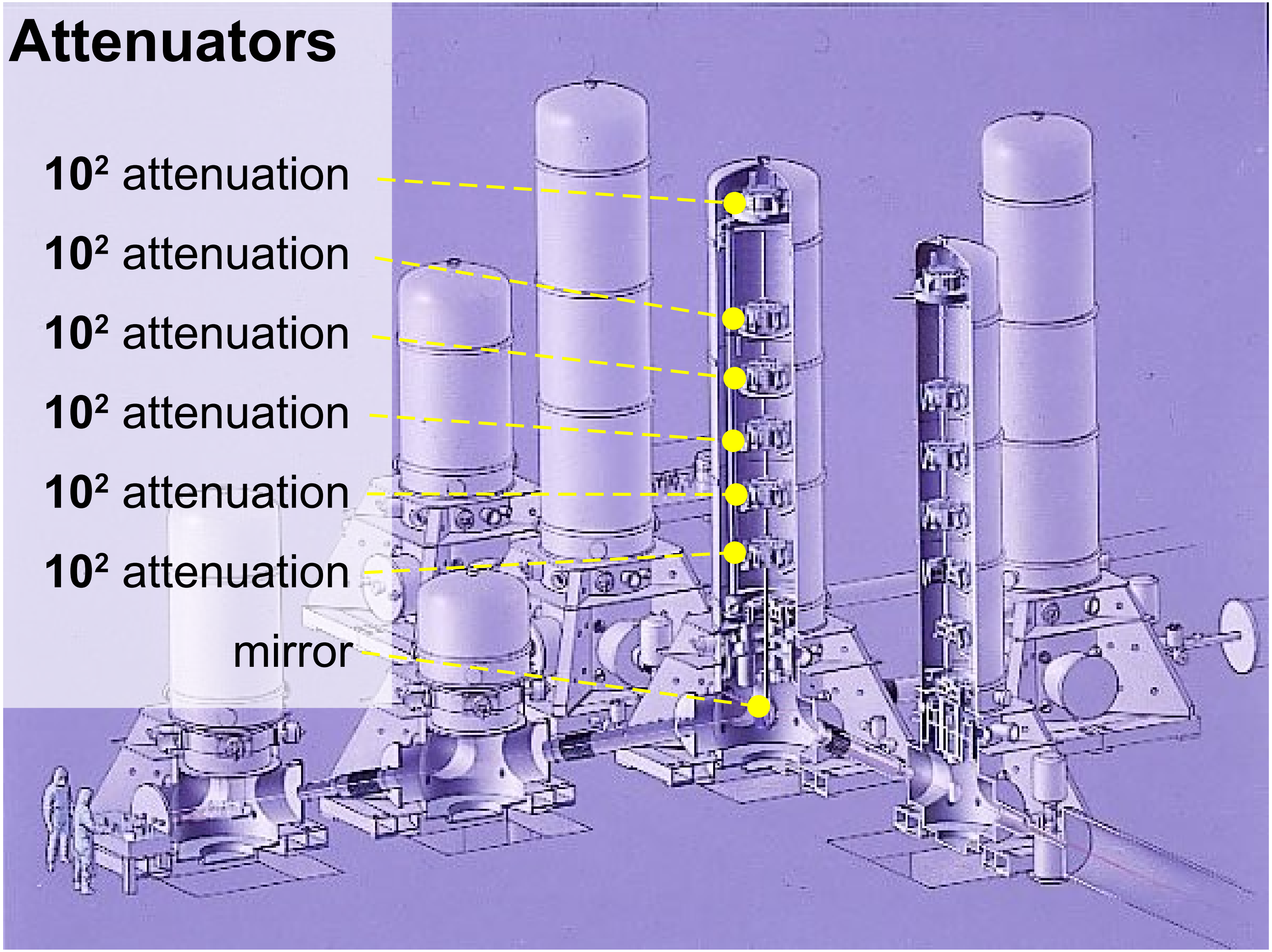
  ↓

  Mirrors have to be
  **more than $10^{10}$ times steadier**
  than their hanging point



# Mechanical isolation of mirrors

- **Super Attenuators**



# Limiting noises

- Extreme techniques have been designed and implemented to *mitigate the different noise sources:*

- **Seismic noise:** at low frequencies the movement of the earth would be dominant → $\mathbf{10^{12}}$ of attenuation from 10 Hz

- **Pressure fluctuations:** is necessary to work under vacuum → P = $10^{-9}$ mbar
(largest ultra-high-vacuum system in Europe)
- **Fluctuations of the laser:** need a stable laser beam (ν, alignment, P...) and "clean" (high content of TEM00)
- **Mirrors quality:** low roughness → $10^{-10}$ m RMS
- ...

# Commissioning

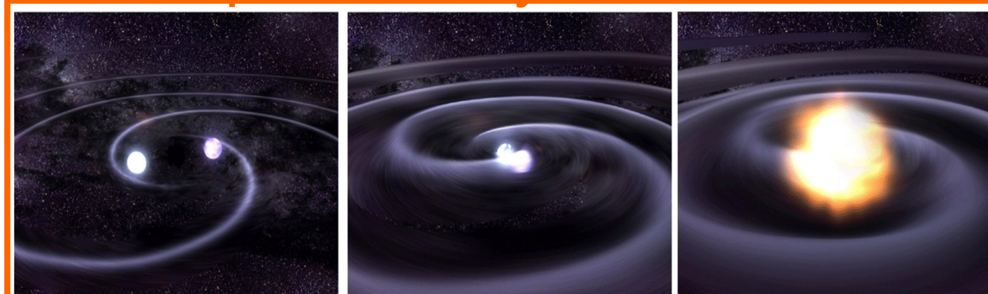
# Sources of GW

**WHY GWs ARE INTERESTING?**

- **New source of astrophysical observations** → complementary to EM spectra + *new phenomena*
- **Test General Relativity**

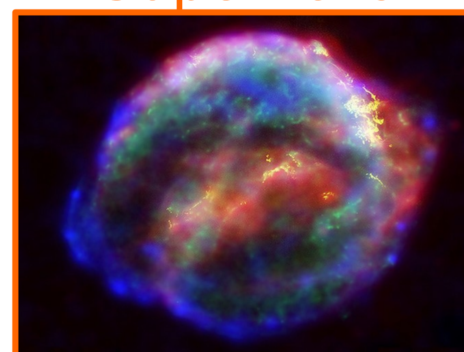
Some **sources** that emit gravitational waves strong enough to be detected by *ground-based GW detectors*

Compact Binary Coalescence



Rotating Neutron Star

Supernova

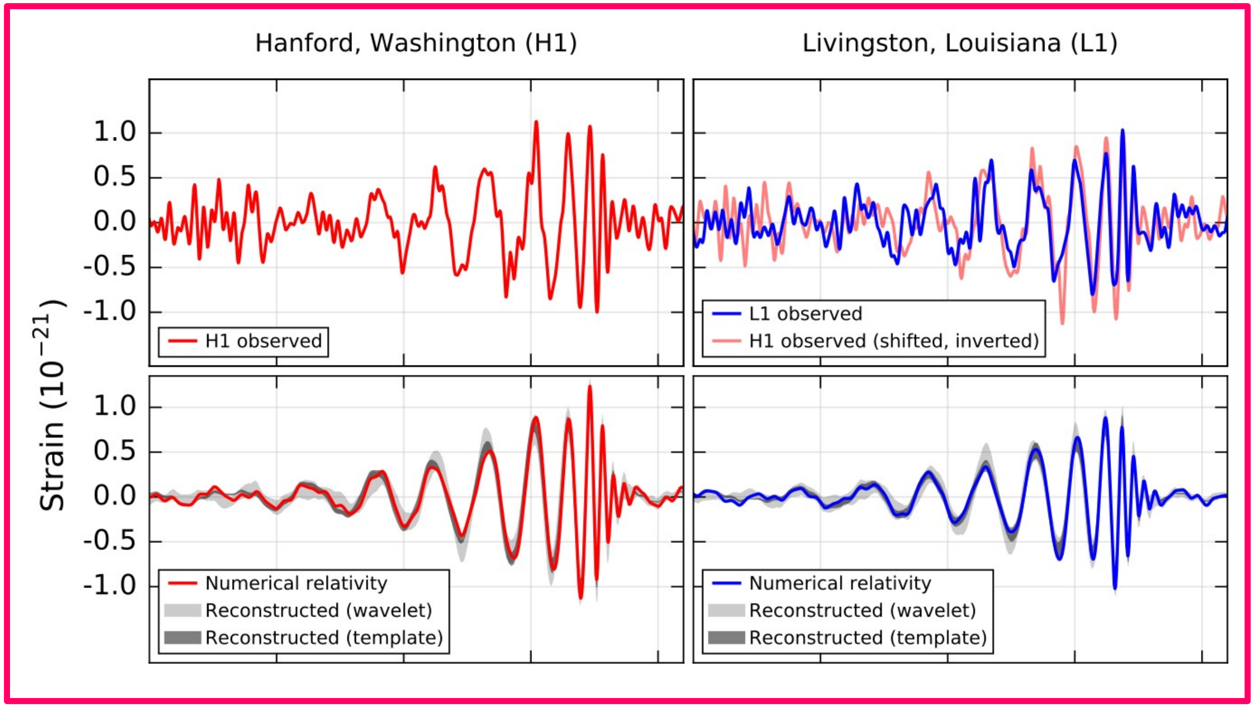


# First detection: GW150914

✓ 14th of September 2015 the Advanced LIGO detectors in the United States, detected a GW for the first time

**GW150914:**

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



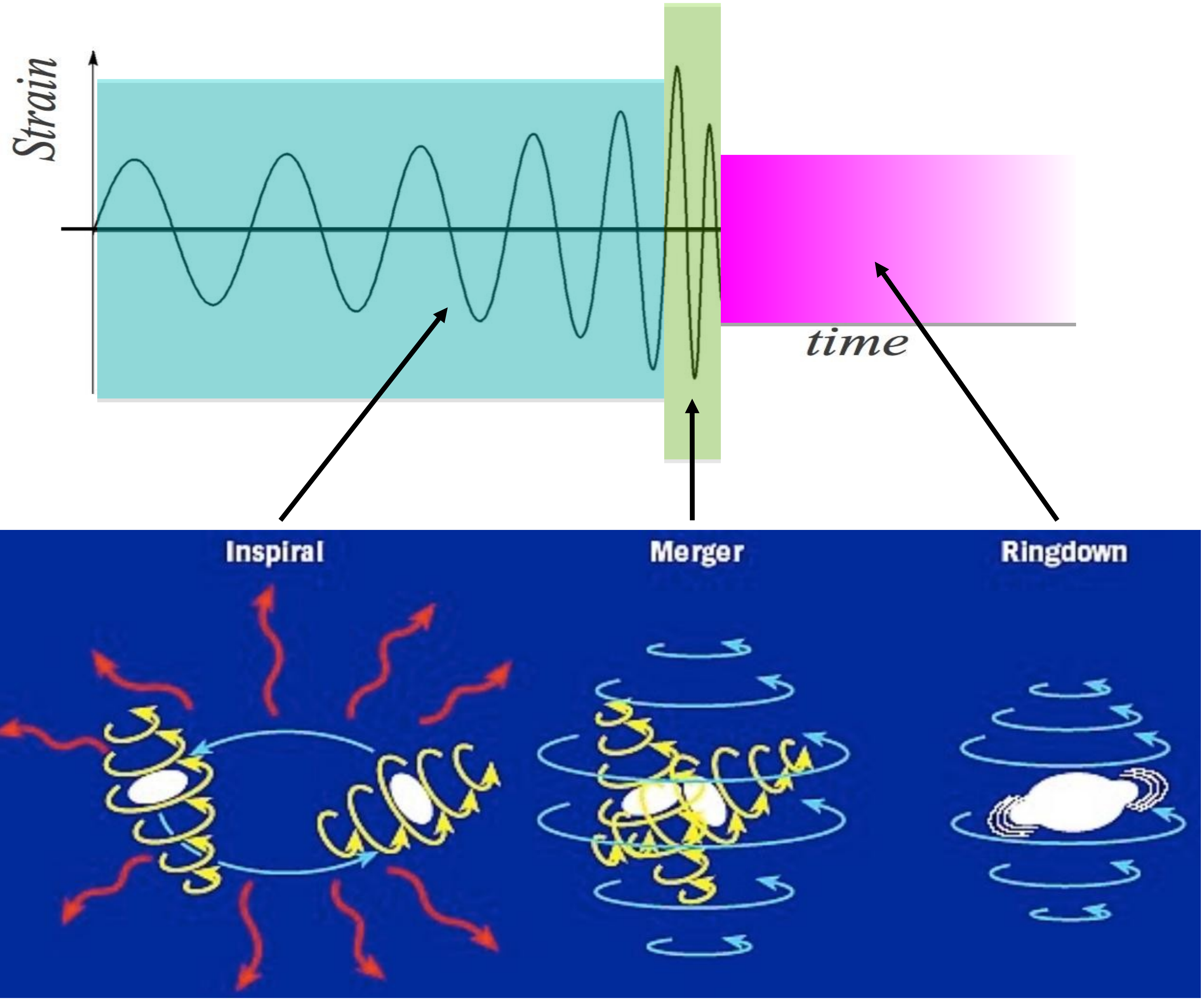

**GW151226:**

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

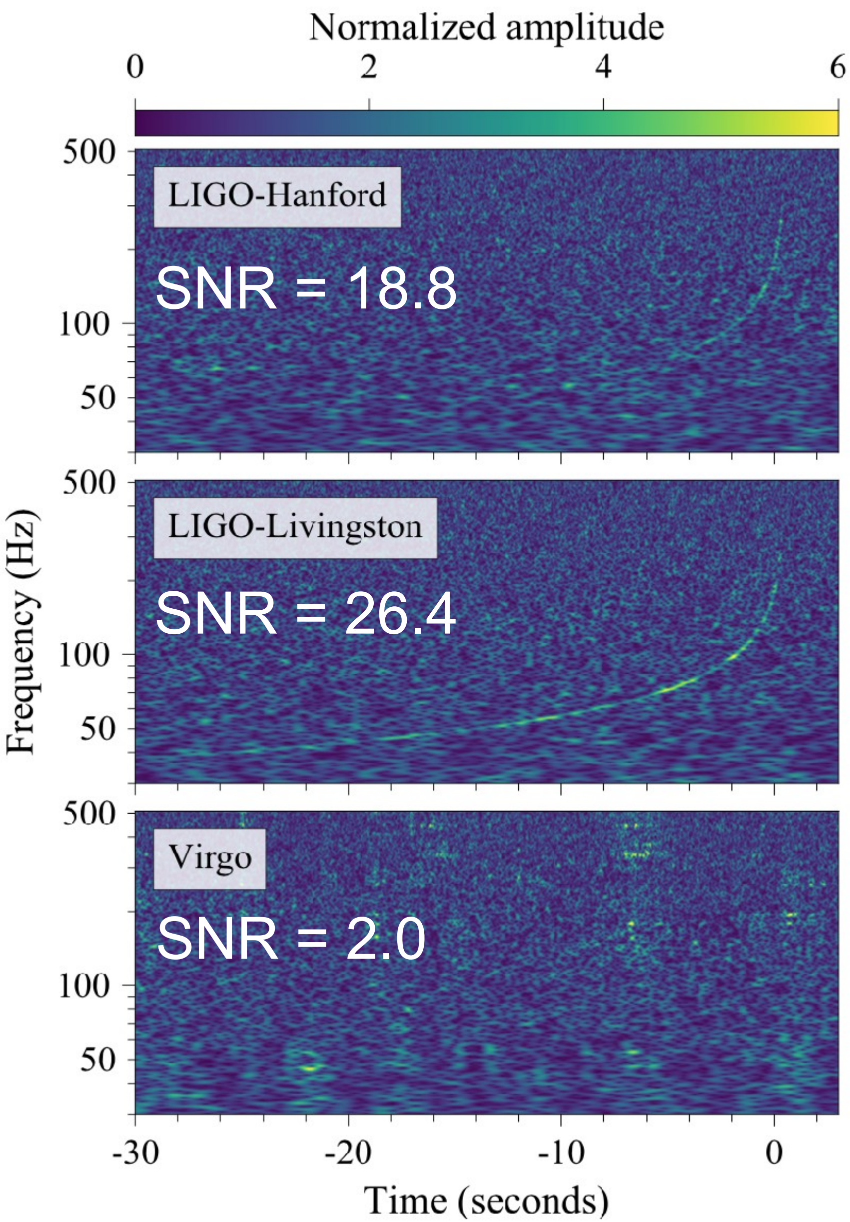
**GW170104:**

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

# Signal of a gravitational wave



# First detection of a BNS: GW170817



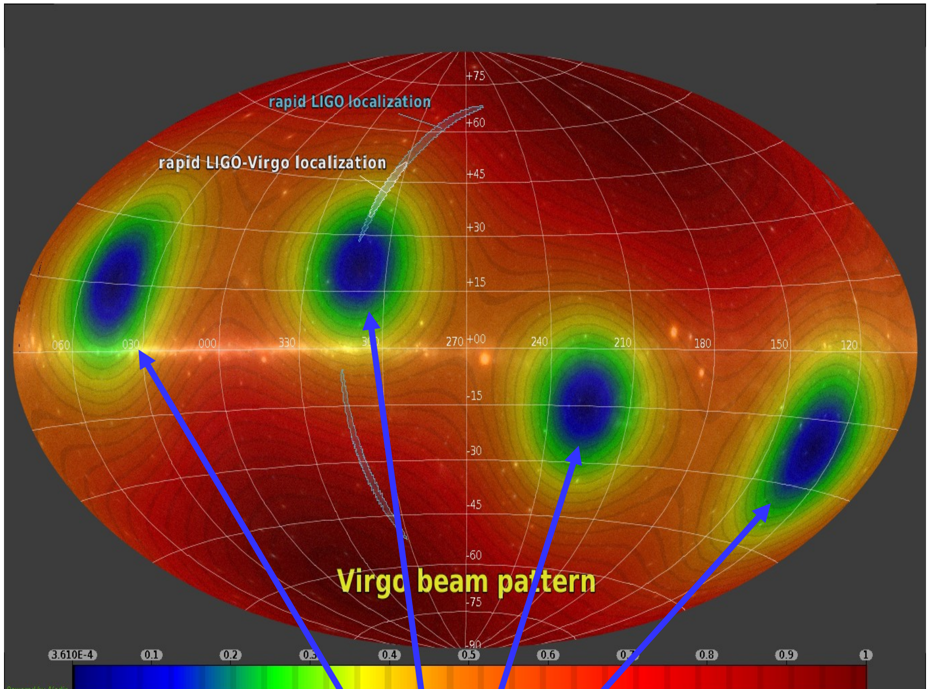

- *Binary Neutron Star*
- Distance: 26-48 Mpc
- Initial masses: 1.36-2.26 and 0.86-1.36 $M_\odot$
- Most energetic event ($3M_\odot c^2$)
- Longest signal (~100 s)

△ Signal is weaker in Virgo (despite an equal sensitivity)

⇓

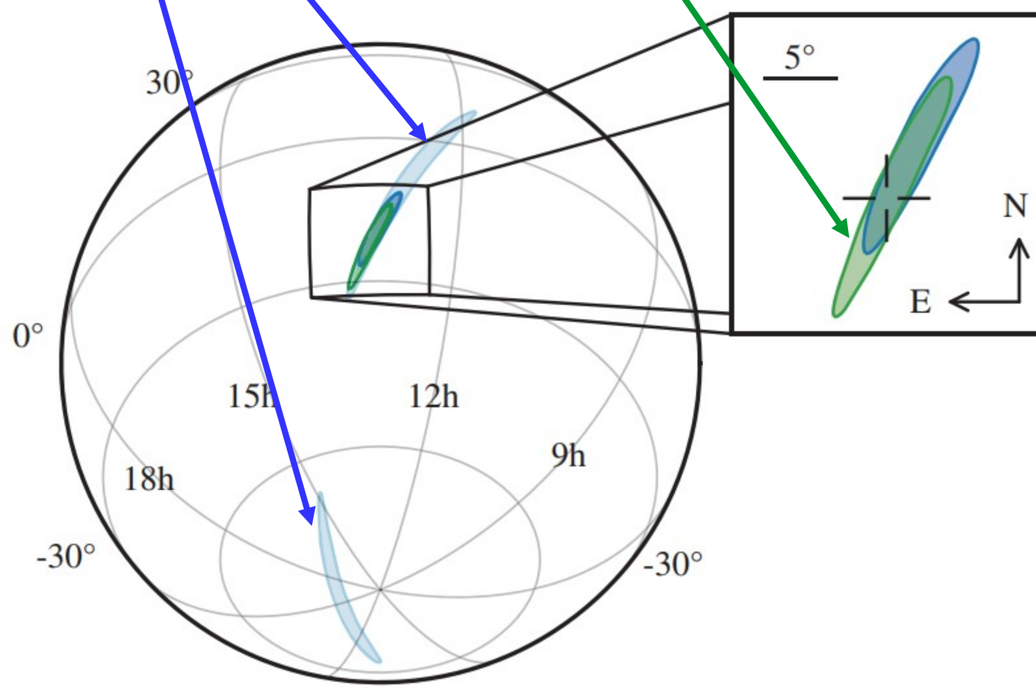
**Antenna pattern of the detector**

# Antenna pattern of the detector



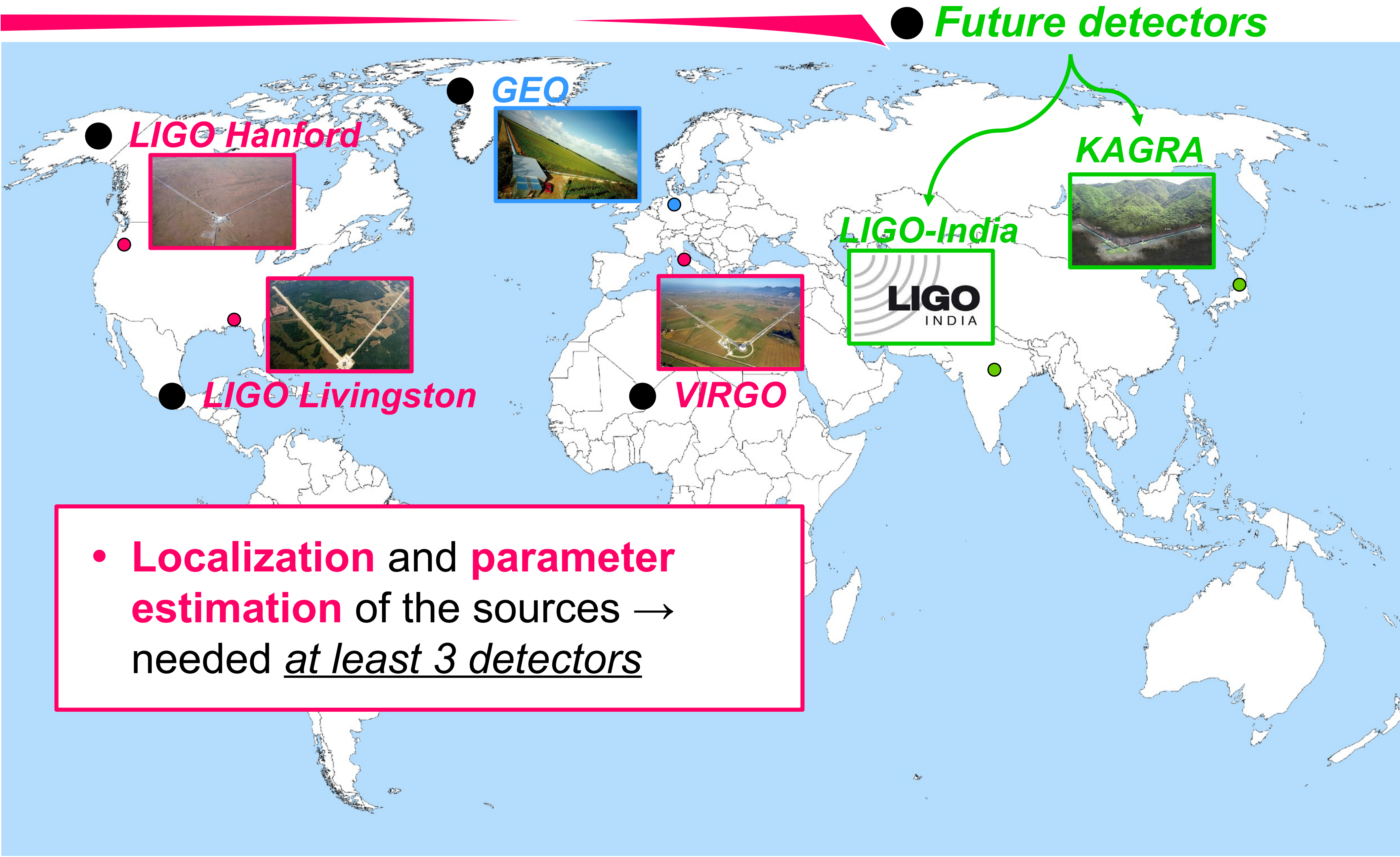

*Sky localization only with LIGO (190 deg$^2$)*

*Sky localization with LIGO+Virgo (28 deg$^2$)*



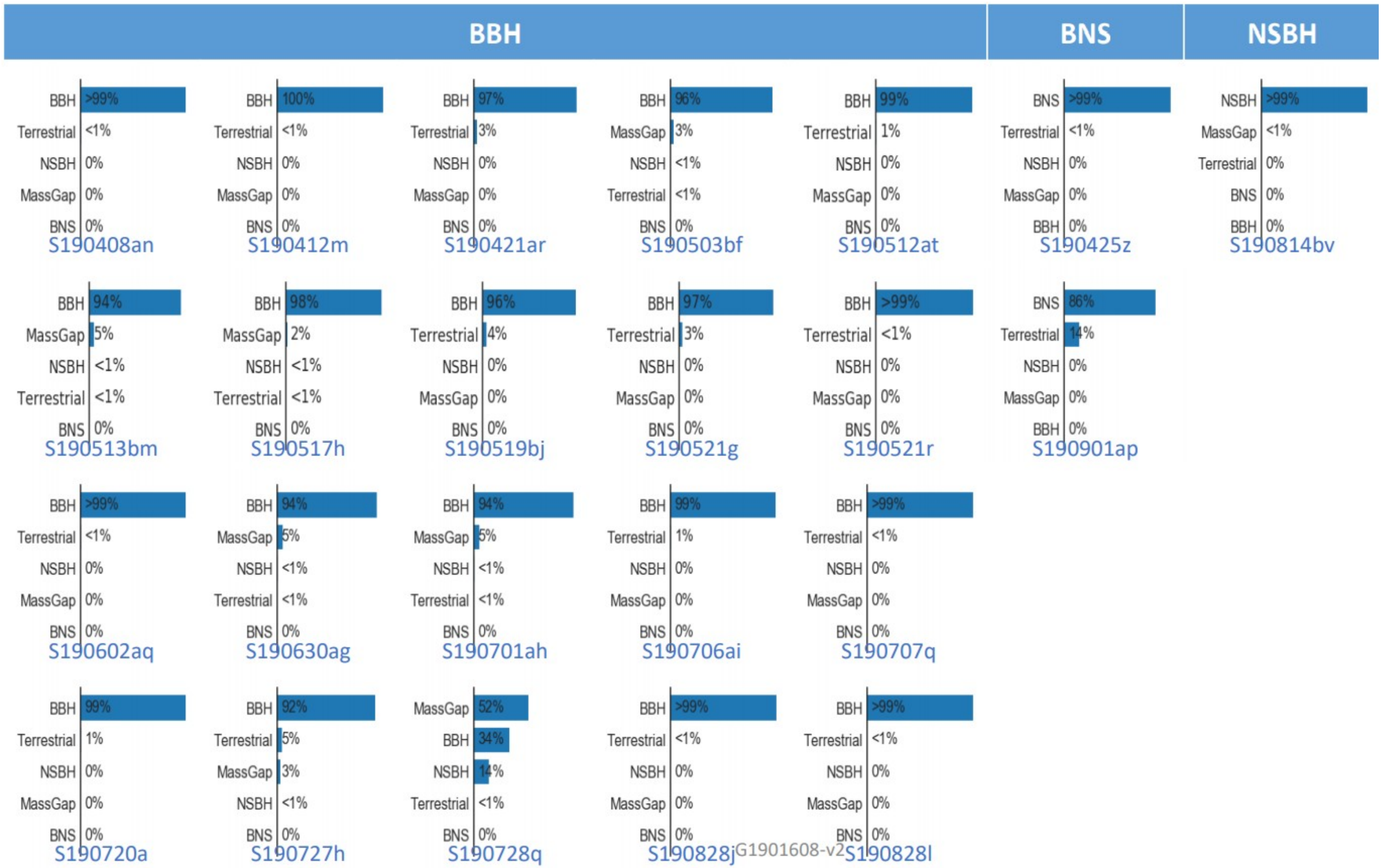

The detector is not equally sensitive in all directions

# GW detectors network




- **Localization** and **parameter estimation** of the sources → needed <u>*at least 3 detectors*</u>

# O3 observation period (last one)
(Apr 2019 - Mar 2020)




More than 1 detection / week

GW astronomy runs


To be continued...