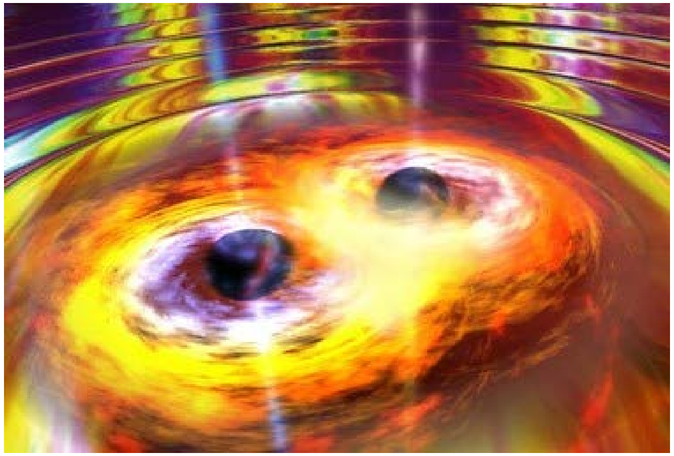
Observation of gravitational waves from a binary black hole merger

GW150914



R. Gouaty

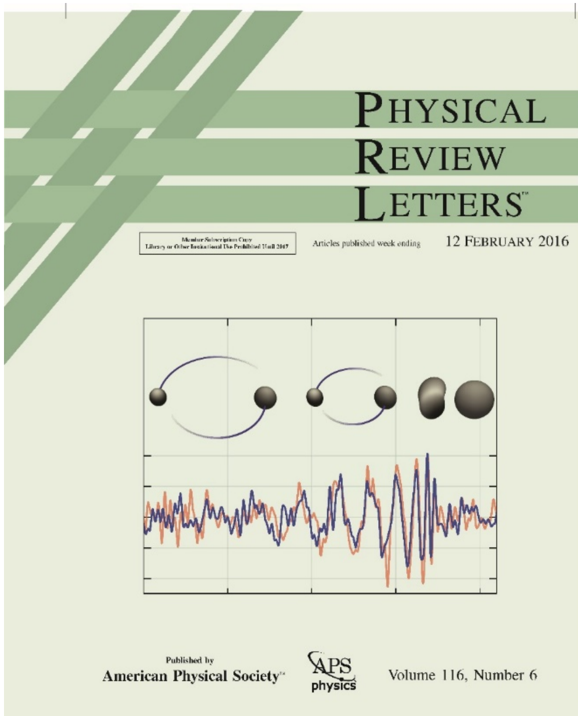
For the LIGO Scientific Collaboration and the Virgo collaboration

Séminaire à l'Ecole Polytechnique Fédérale de Lausanne, 28 avril 2016

Virgo web site: http://public.virgo-gw.eu/
LIGO web site: http://www.ligo.org/

Outline

- Gravitation
- Gravitational waves
- An experimental challenge
- GW150914



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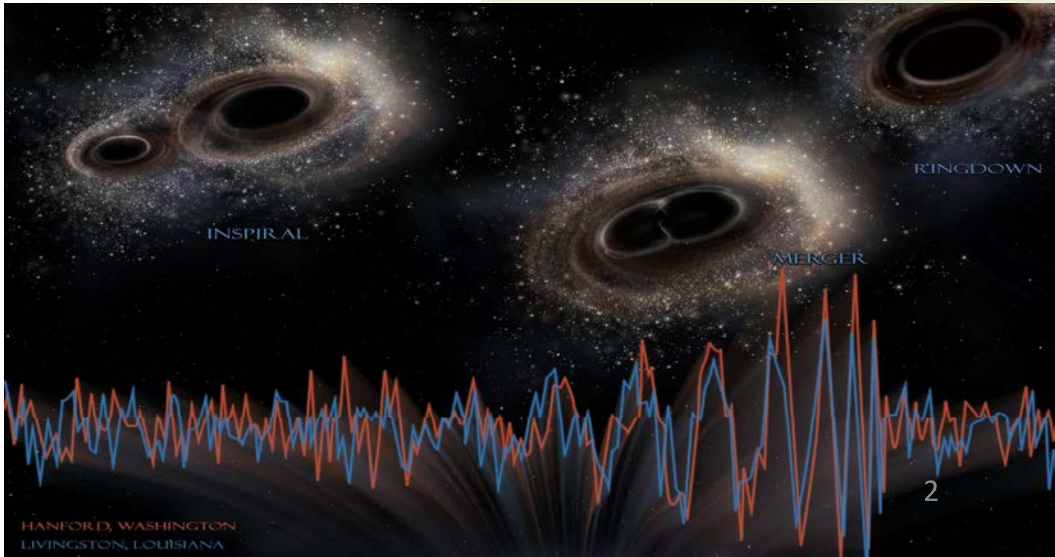


Fundamental interactions

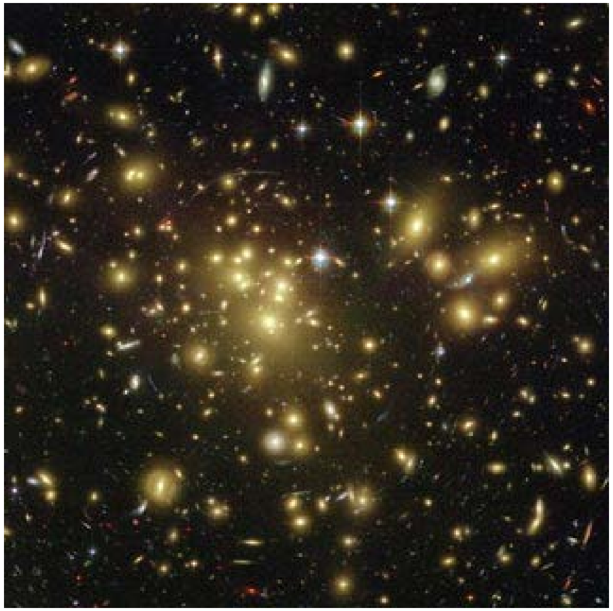
- Gravitation : one of the four fundamental interactions of nature
- The weakest

TYPE	RELATIVE STRENGTH	Example of fields of application
STRONG	~ 1	Nucleus
ELECTROMAGNETIC	~ 10^{-2}	electrons, light, chemistry
WEAK	~ 10^{-6}	β decay solar energy
GRAVITATION	~ 10^{-38}	Gravity planetary systems

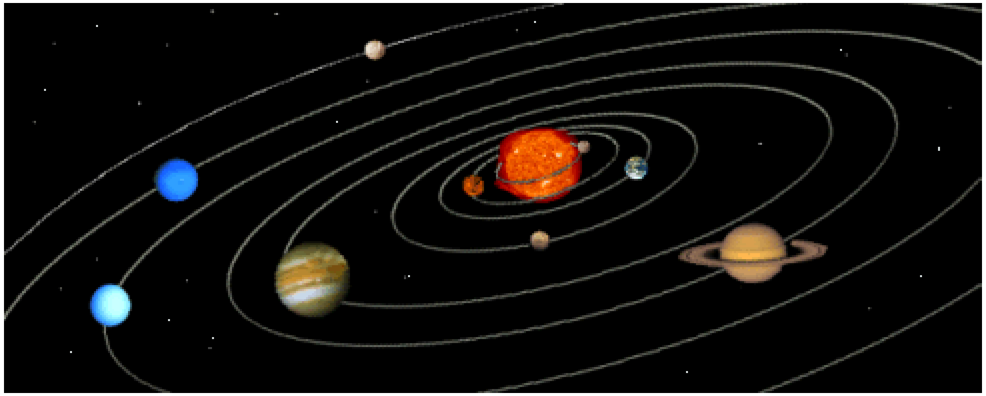
Gravitation

- ❑ Strength ratio between electromagnetic & gravitational interactions between 2 electrons ~ $4 \cdot 10^{42}$!


- ❑ Gravity



- ❑ Planetary systems
- ❑ Large scale structure of the Universe



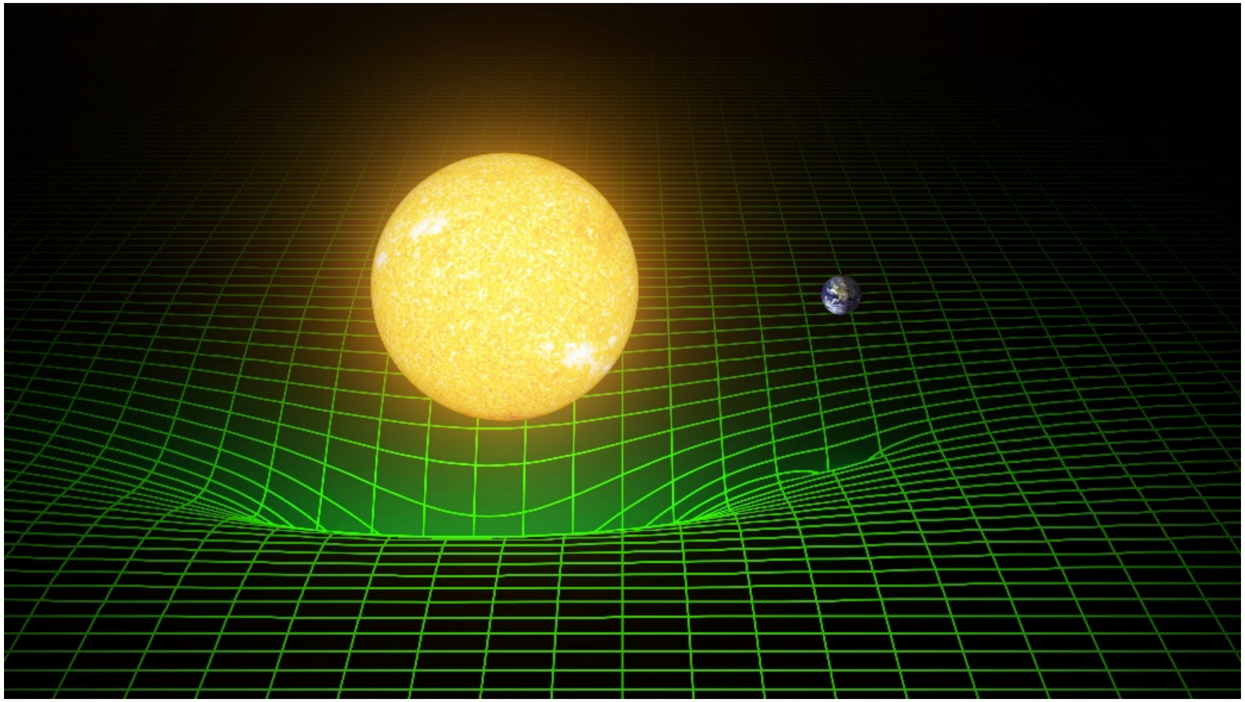
Newton vs Einstein

- ❑ Classical theory of gravitation
  - ➢ Flat space, absolute time
  - ➢ $F = G\, m_1\, m_2 / r^2$
  - ➢ Instantaneous interaction between distant masses

- ❑ Modern theory of gravitation (General Relativity)
  - ➢ Space and time are linked, dynamical space-time
  - ➢ **Equivalence principle** :

    inertial mass = gravitational mass
  - ➢ $G_{\mu\nu} = 8\pi\, G\, T_{\mu\nu} / c^4$
    - $G_{\mu\nu}$ curvature tensor
    - $T_{\mu\nu}$ energy momentum tensor
    - J. A. Wheeler : ***"Space tells matter how to move and matter tells space how to curve"***

Einstein's gravitation

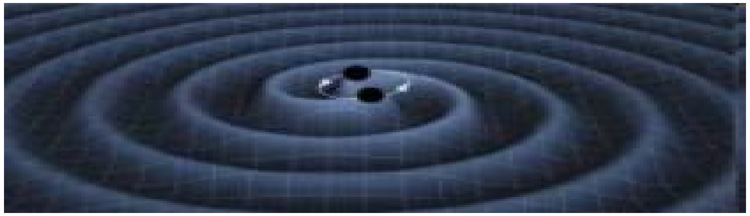


- ☐ Gravitational interaction is the manifestation of space-time curvature

- ☐ Accelerated massive bodies emit a radiation
  - ➢ Analogy with electro-magnetic waves:

    ➔ Transversal waves propagating at speed of light
  - ➢ Gravitation only attractive ➔ quadrupolar radiation

Gravitational waves

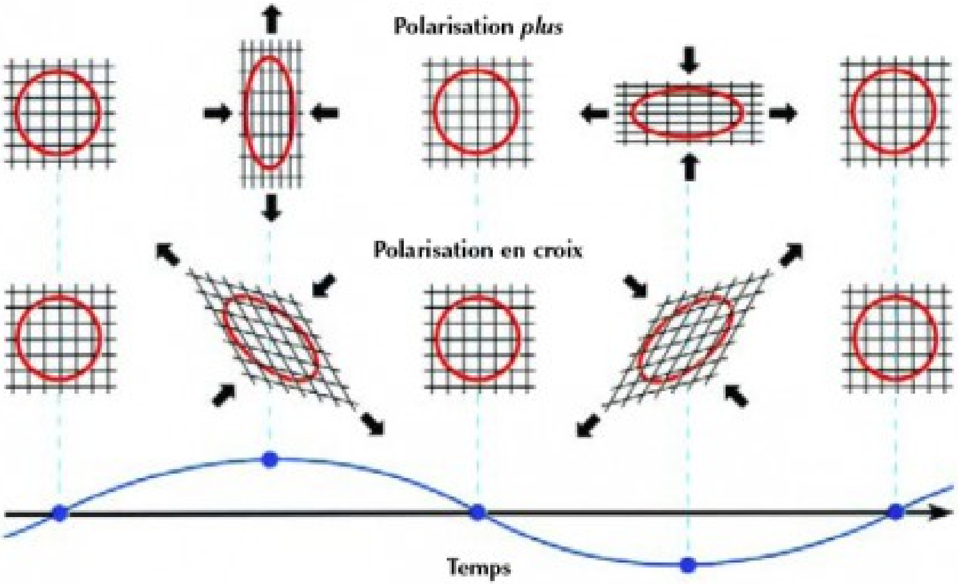


- ☐ **Fluctuations of space-time curvature**

→ Fluctuations in the metric

→ Distance separating free fall masses changes

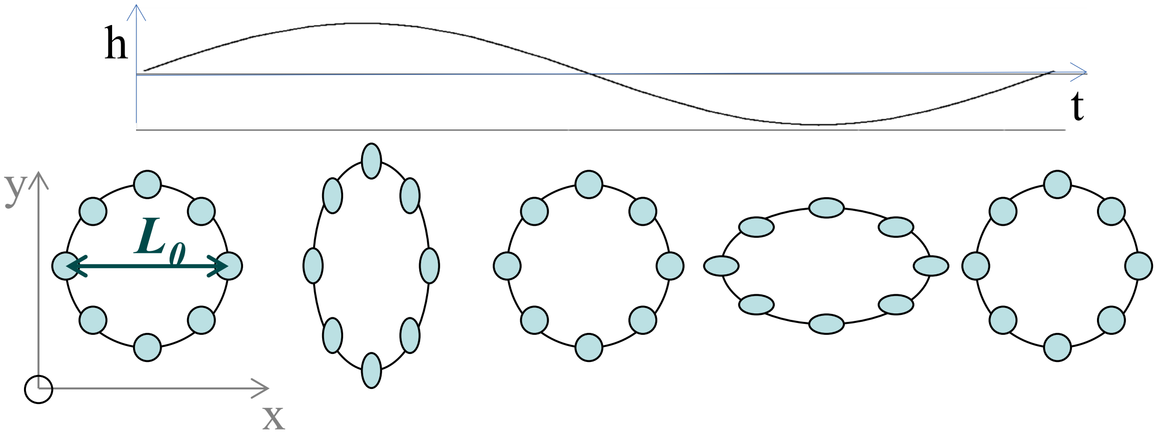
- ☐ Combination of two polarization states (+ and x)



Gravitational waves

Gravitational waves amplitude

- GW amplitude:



$$\delta L(t) = \frac{1}{2} h(t) L_0$$

Length variation proportional to GW amplitude and to L_0

- For the observer:

$$h \propto \frac{1}{d}$$

The amplitude decreases with the distance separating the source from the observer

- Which sources?
  - Generate GW in the lab? → NO (too weak amplitude)
  - **Astrophysical sources** (huge masses and accelerations)
    - Despite the distance penalty

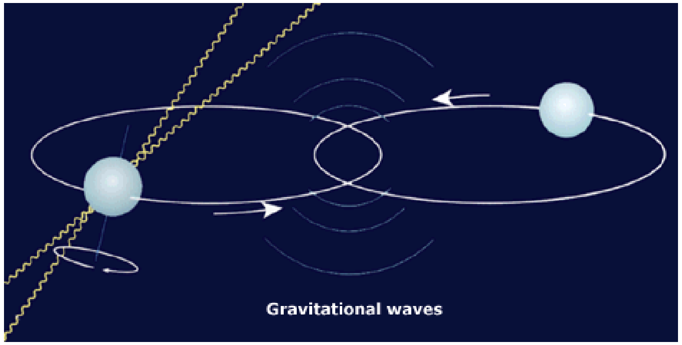
An interesting object: PSR 1913+16

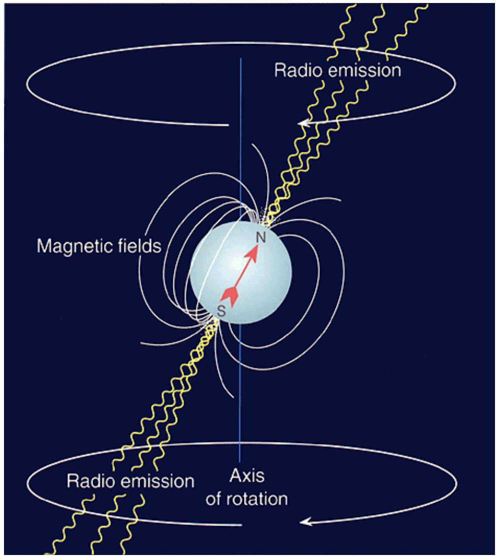
- Discovered by R.Hulse and J.Taylor in 1974
  - Two neutron stars orbiting around each others
    - Neutron star: ~1.4 solar mass within 30 km diameter!
    - Orbital period of binary system ~ 8 hours
  - One of the stars is a pulsar
    - Pulsar : neutron star rotating and emitting radio waves along its magnetic axis

      ➔Like a lighthouse:

      The observer receives radio pulses
    - Measurement of arrival time of the pulses:

      → gives all system parameters
- Nobel prize in 1993



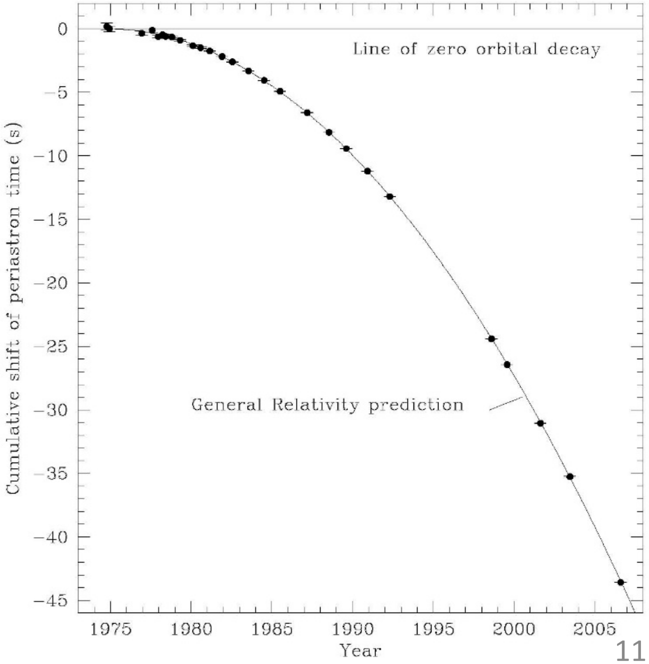


First evidence for gravitational waves

- Orbital period decreasing over time:
  - Two stars getting closer to each others

- System losing energy by emission of GW
  - Good agreement with GR prediction (within 0.1%)

- An indirect evidence:
  - Remained to highlight **physical effects** of GW



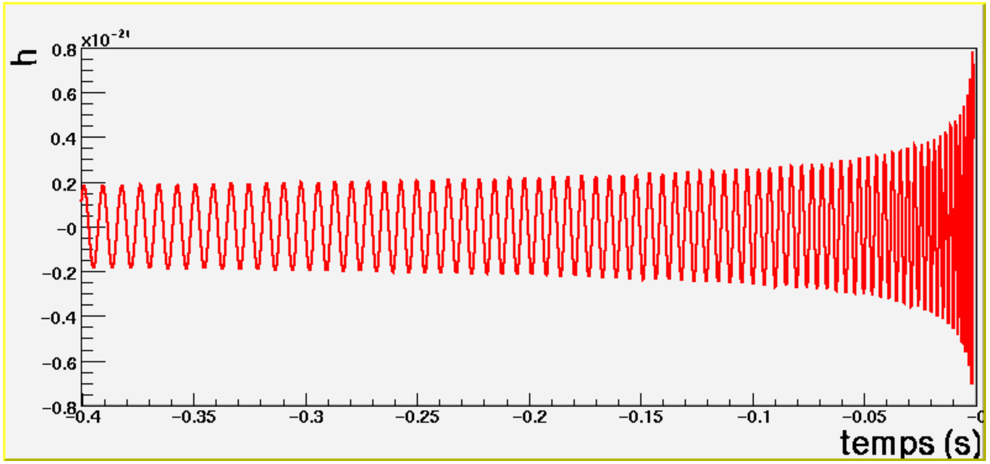
Which detectable sources ?

- Frequency range of ground-based gravitational-wave interferometers:
  10 Hz – 10 kHz
  - This is also the frequency range where human ears are sensitive
    - Low frequency = deep sound
    - High frequency = high-pitched sound
- Frequency of GW emitted by PSR 1913+16: ~ 0.07 mHz
  - Undetectable by ground-based detectors
- Need to find other sources
  - Within the accessible frequency range
  - Detectable with a realistic sensitivity
  - Phenomena occuring at sufficiently high rate

Sources : coalescing binaries

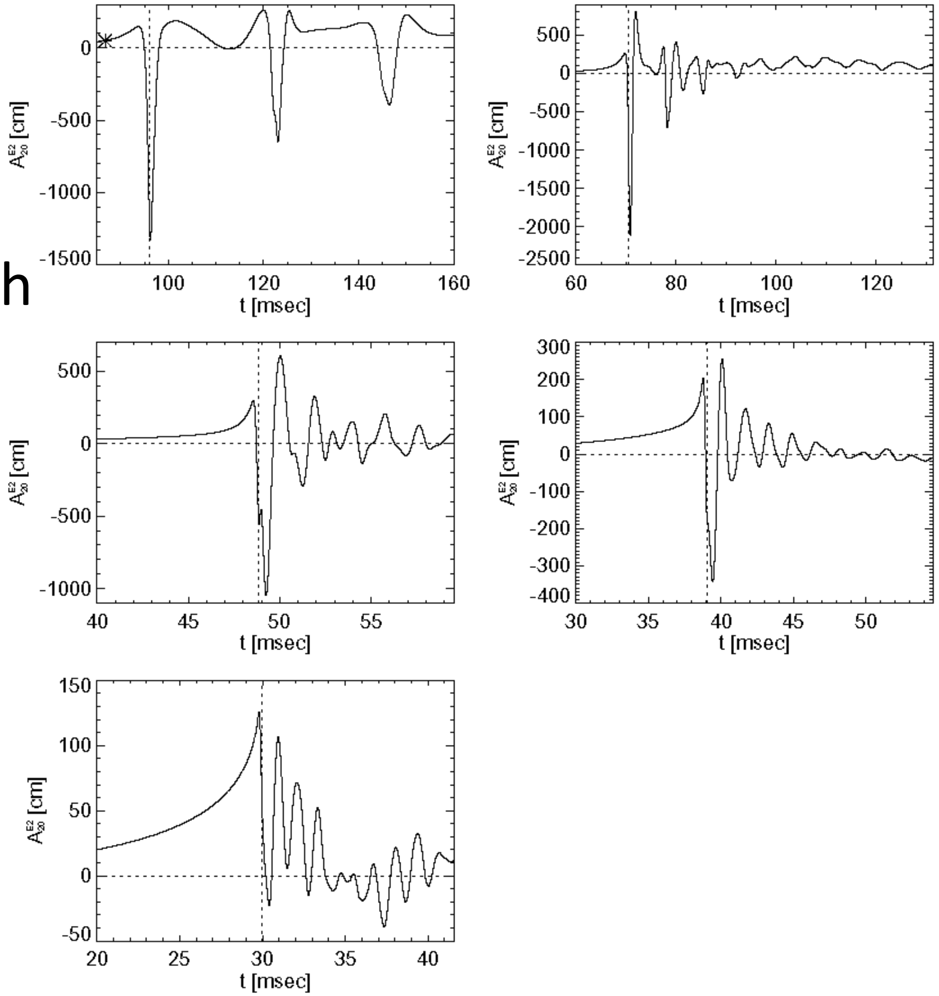
- Binary systems of compact stars at the end of their evolution
  - Neutron stars and black holes

- Very rare phenomenum in our Galaxy
  - A few tens per million years
- Typical amplitude (for neutron stars)
  - $h \sim 10^{-22}$ à 20 Mpc
  - 1 parsec = 3.26 light years
- Very distinctive waveform



Sources : supernovae

Examples of waveforms



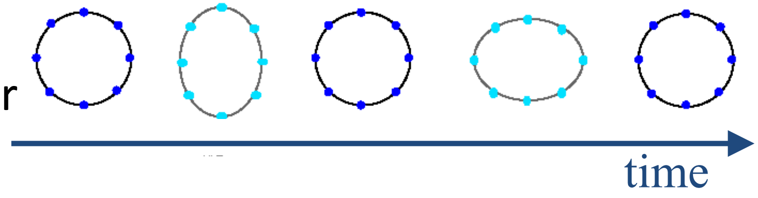
- Gravitational collapse of massive stars
- Can potentially be associated with GW radiation
  - Uncertainty on the amplitude
    - $h \sim 10^{-21}$ à 10 kpc
  - Difficult to predict waveform
  - Rare phenomenum in the Galaxy
    - 3 - 4 / century

An experimental challenge

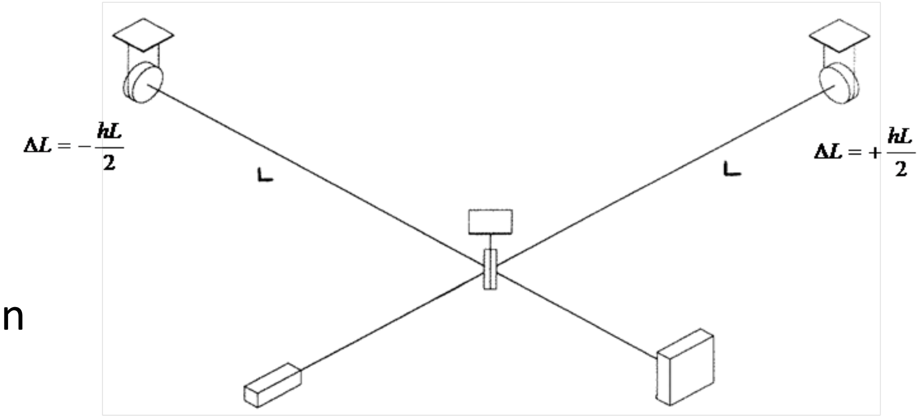
- ❑ Why is it a challenge?
  - ➢ Measure a relative variation of length ~ 10^{-23}
  - ≡ Measure the distance Earth – Moon with an accuracy roughly equal to the size of a proton!
- ❑ A 50 years quest:
  - ➢ First with « resonant bars » detectors
  - ➢ For the last ~ 20 years, with gravitational-wave interferometers

Gravitational-wave interferometer

- Measure a variation of distance between masses
  - Measure the light travel time to propagate over this distance
  - Laser interferometry is an appropriate technique
    - Comparative measurement
    - Suspended mirrors = free fall test masses



- Michelson interferometer well suited:
  - Effect of a gravitational wave is in opposition between 2 perpendicular axes
  - Light intensity of interfering beams is related to the difference of optical path length in the 2 arms

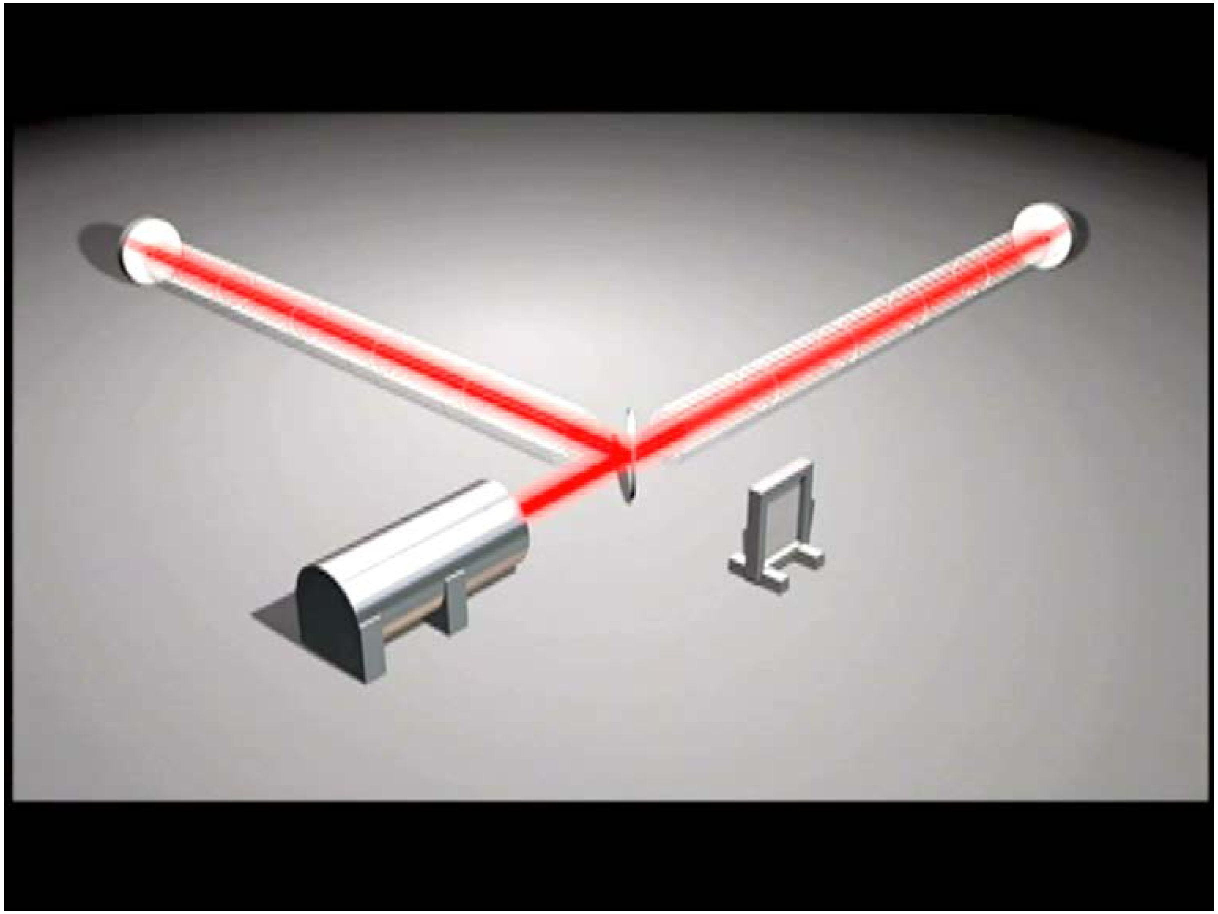


We need a big interferometer:

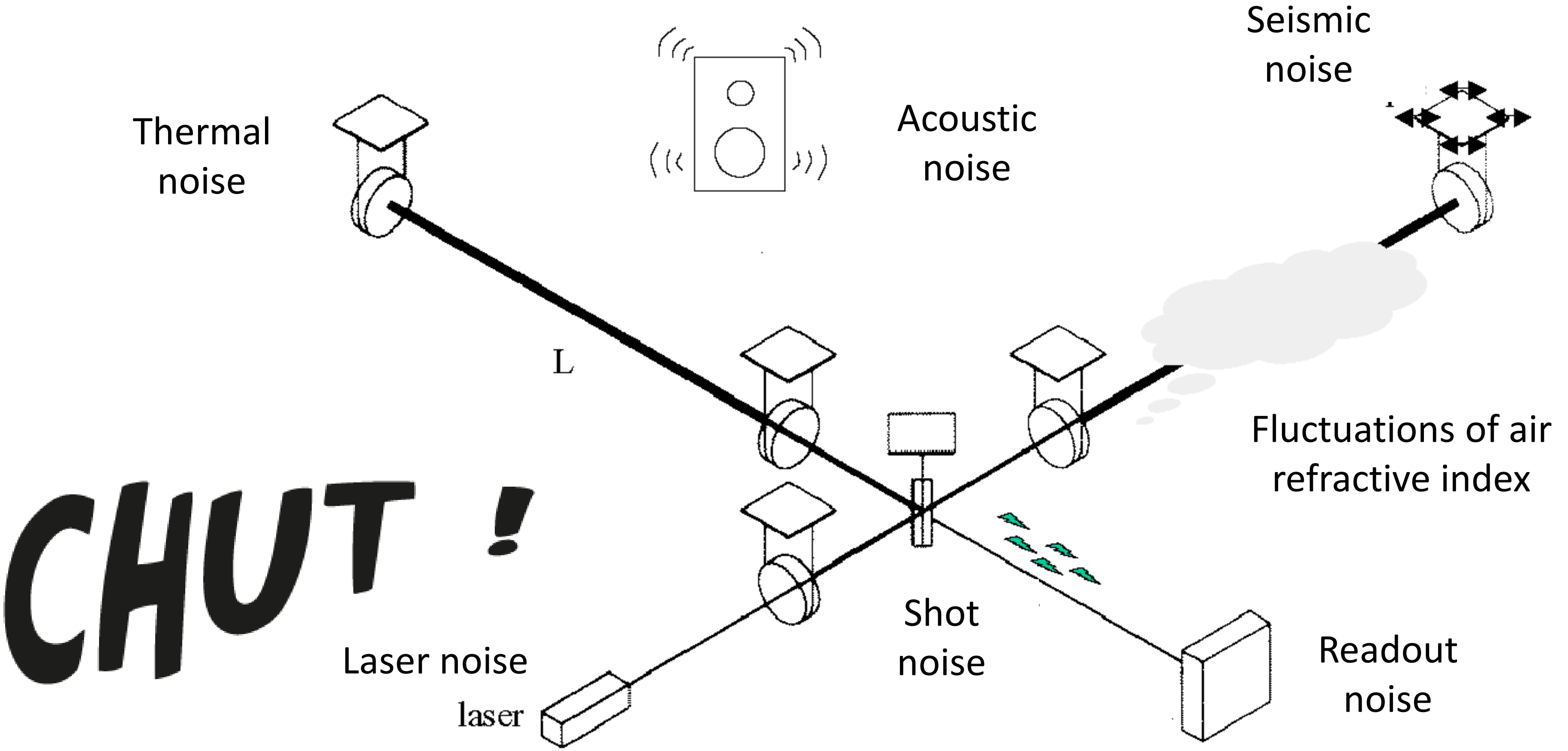
ΔL proportional to L

➔ need several km arms!

Gravitational-wave interferometer



Noise sources



Thermal noise

Acoustic noise

Seismic noise

Fluctuations of air refractive index

Laser noise

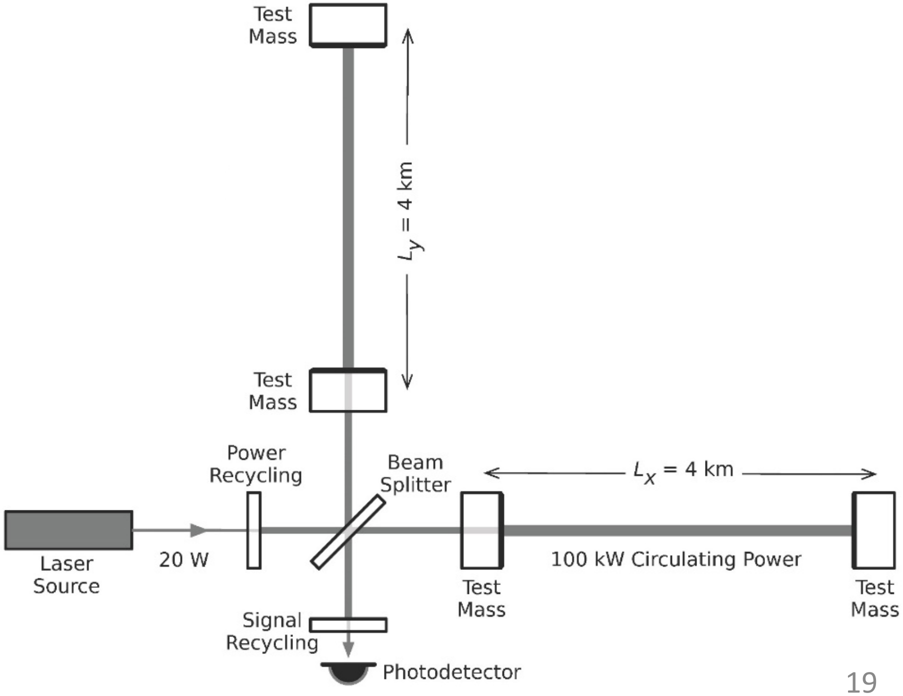
Shot noise

Readout noise

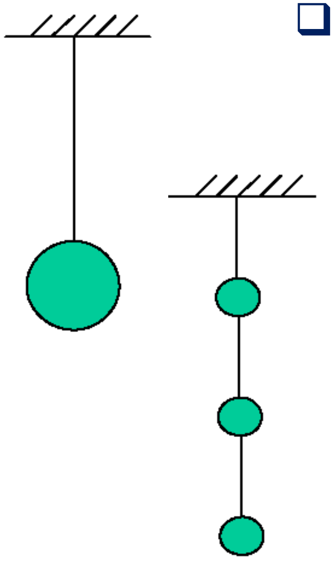
Shot noise

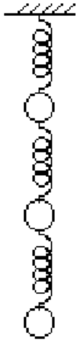
- Measuring light intensity = counting photons
  - Photons are quantum particles: cannot be counted exactly: $N \pm \sqrt{N}$
  - Shot noise $\propto \sqrt{P}$ with P: light power
  - GW signal $\propto P$
  - Signal to noise ratio $\propto \sqrt{P}$

- More complex optical configuration
  - Increase power circulating in the interferometer
  - Increase effective arm length

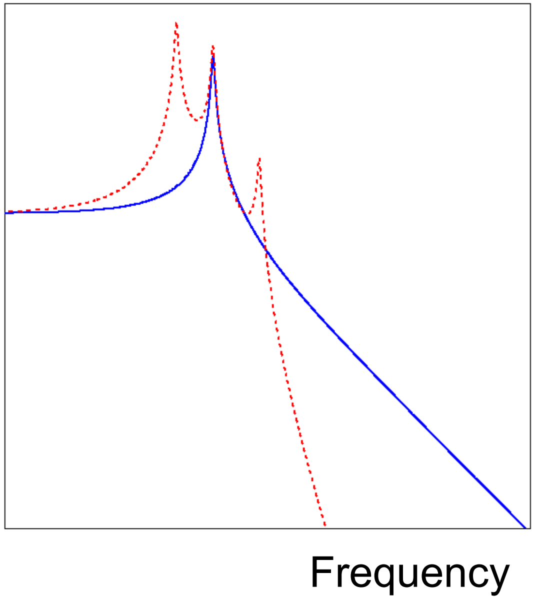


Seismic noise





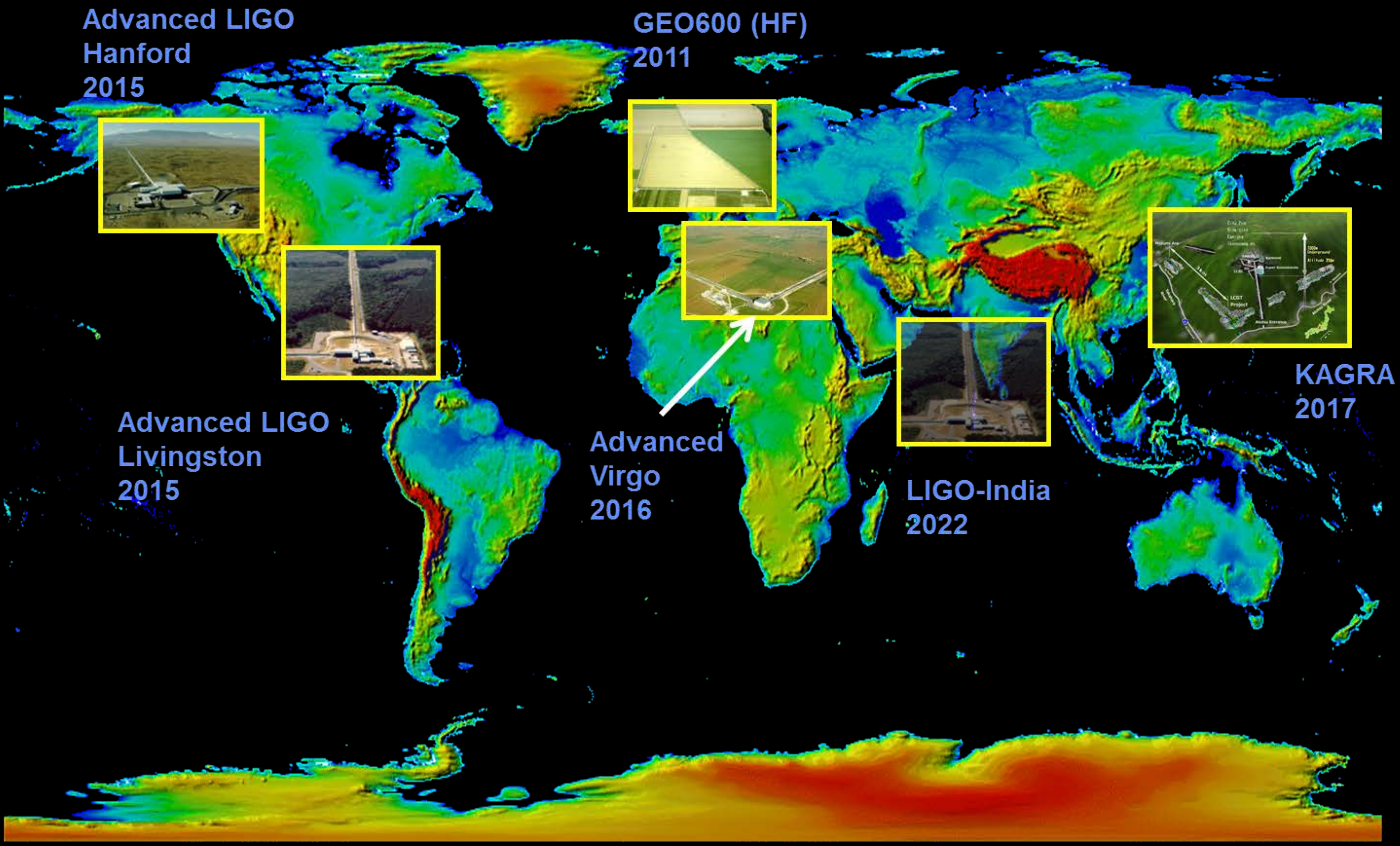
- ❑ A suspended mirror is isolated from vibrations
  - ➢ For f > pendulum resonance frequency
  - ➢ Horizontal ground motion is filtered in$1/f^2$
  - ➢ Several pendula in series
  - ➢ Need also to attenuate vertical motion



- ❑ Mirrors are moving at low frequency ➔ is it an issue?
  - ➢ No
    - ▪ Noise at low frequency does not mask a signal at higher frequency
  - ➢ But actually, yes…
    - ▪ The interferometer must me maintained at its working point:

    → conditions of interference must be controlled

The detector network



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

KAGRA
2017

Advanced LIGO
Livingston
2015

Advanced
Virgo
2016

LIGO-India
2022

LIGO

2 interferometers - 4 km arms

- Louisiana
- Washington State
- A third one will be installed in India

Virgo

- CNRS + INFN (+ Netherlands, Hungary, Poland)
- 3 km, near Pisa in Italy

The benefits of the network

- An interferometer works more like a ear than a telescope

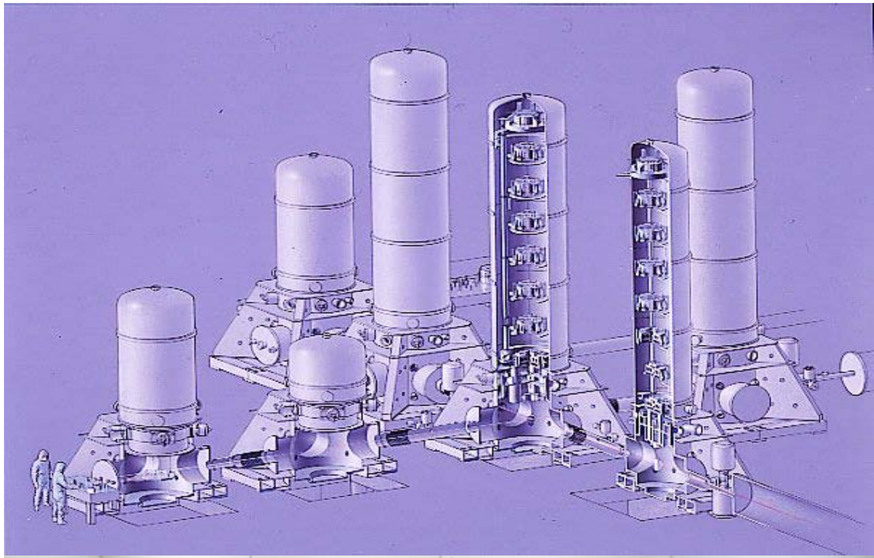
  - A single detector cannot localize the source
  - Need to compare the signals found in coincidence between several detectors (triangulation):

    → allow to point towards the source position in the sky
- Looking for rare and weak signals: can be hidden in detector noise

    → requires observation in coincidence between at least 2 detectors
- Since 2007, Virgo and LIGO share their data and analyze them jointly

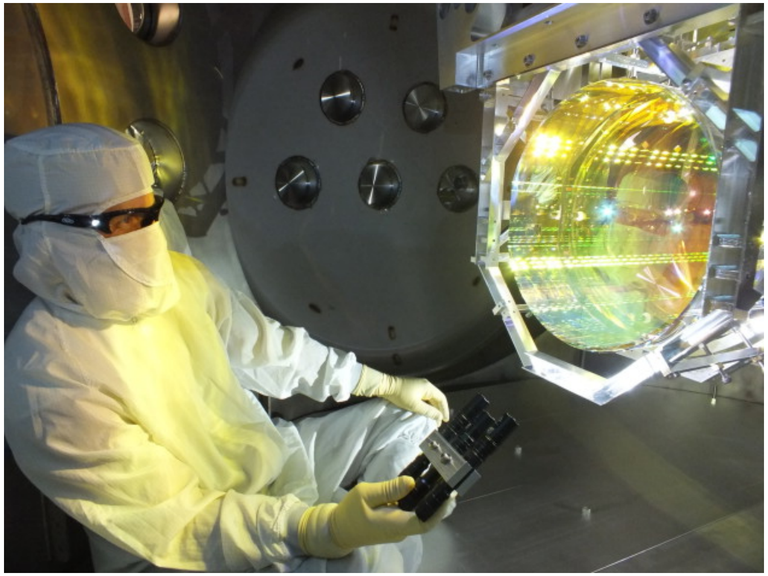
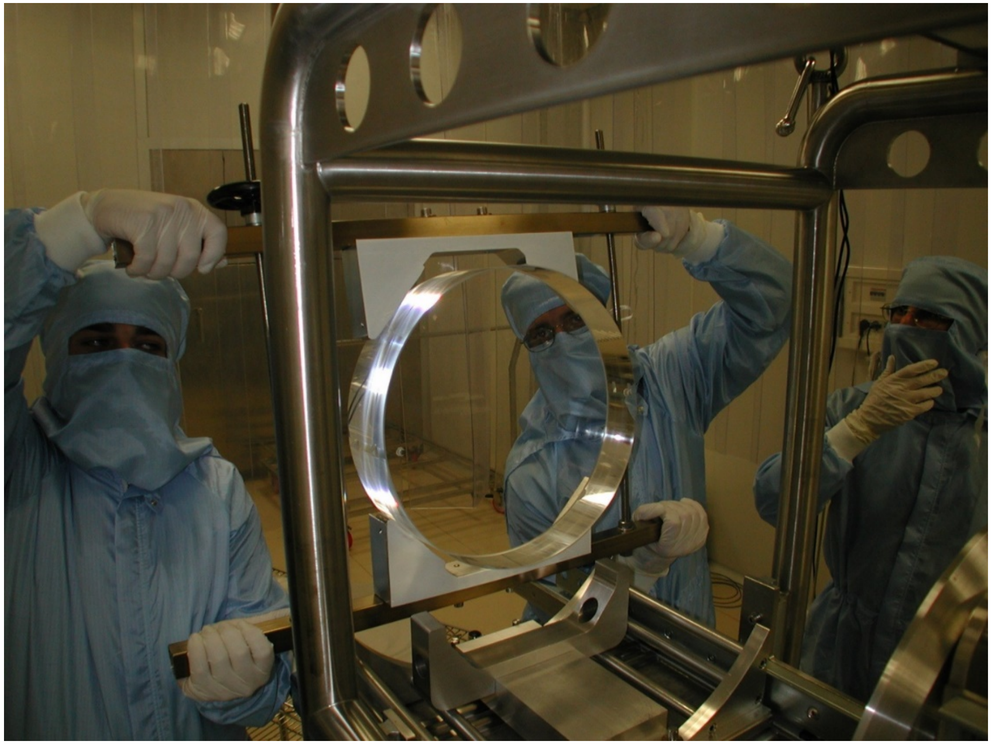
Under (ultra high) vacuum

- ☐ Isolate mirrors from acoustic noise
- ☐ Avoid measurement noise due to fluctuations of refraction index in air
- ☐ Keep mirrors clean



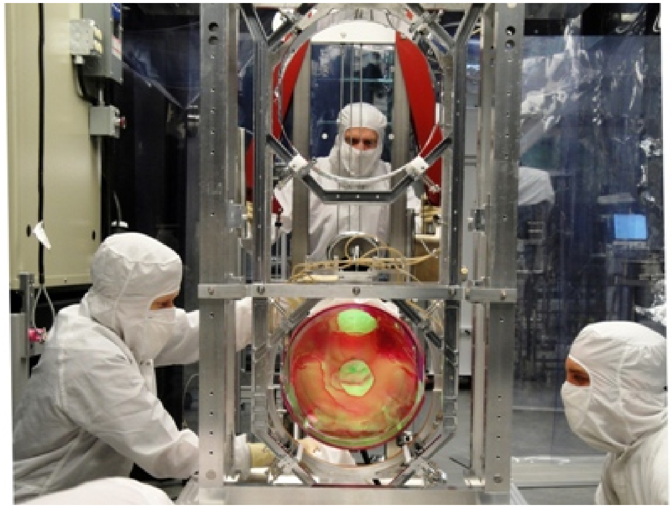
Mirrors

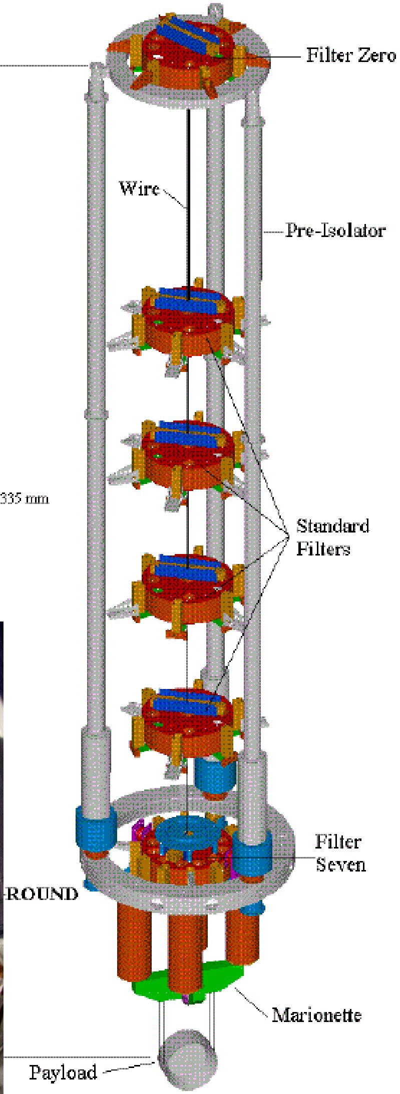
- ❑ Large mirrors
- ❑ Very high quality: almost no imperfections
- ❑ Handled in clean rooms

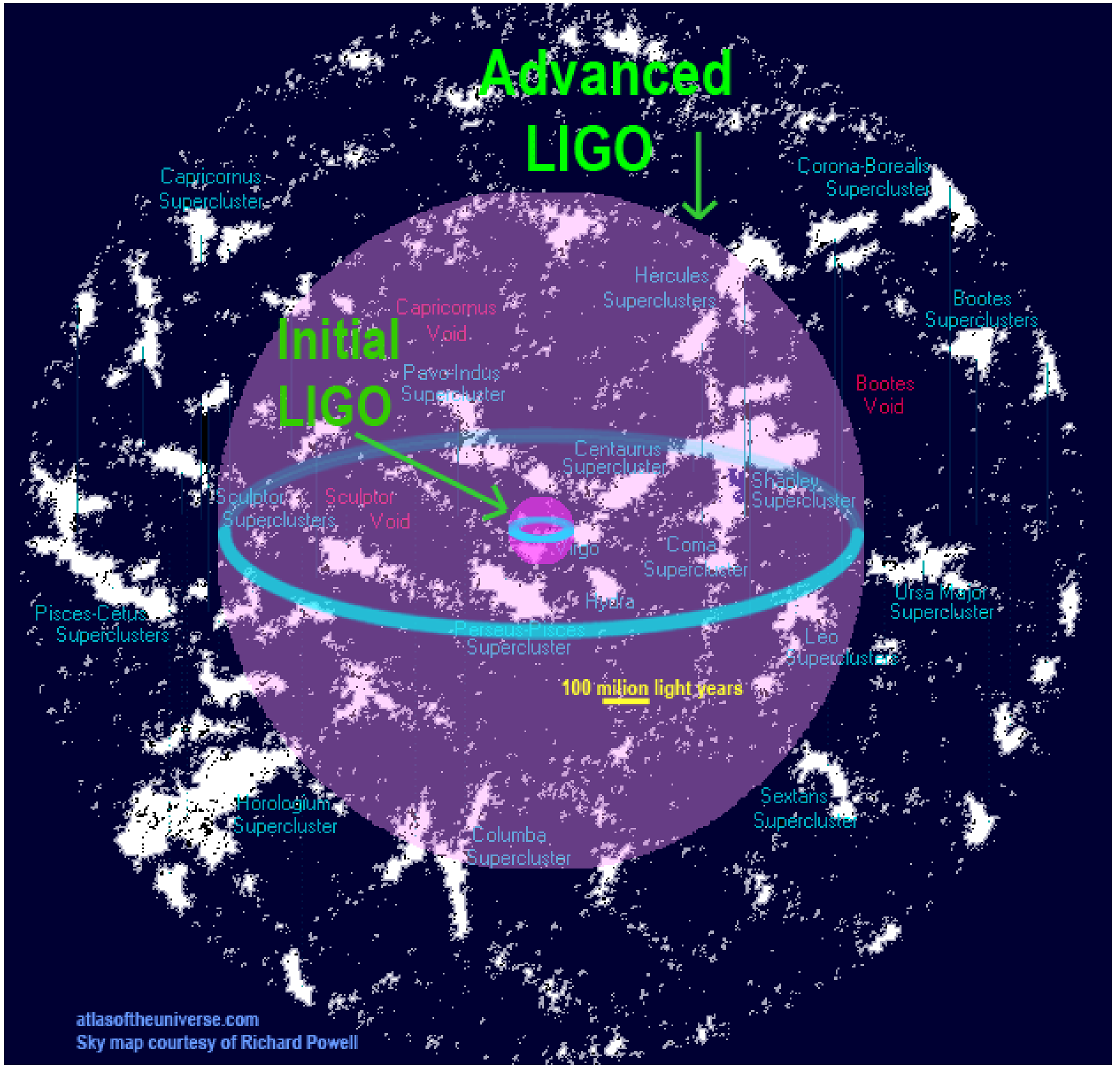
Coating of mirror surfaces performed at LMA (Laboratoire des Matériaux Avancés) in Lyon

Seismic isolation





From the first to the second generation of detectors



atlasoftheuniverse.com
Sky map courtesy of Richard Powell

On Feb 11, the LIGO and Virgo collaborations have announced the detection of

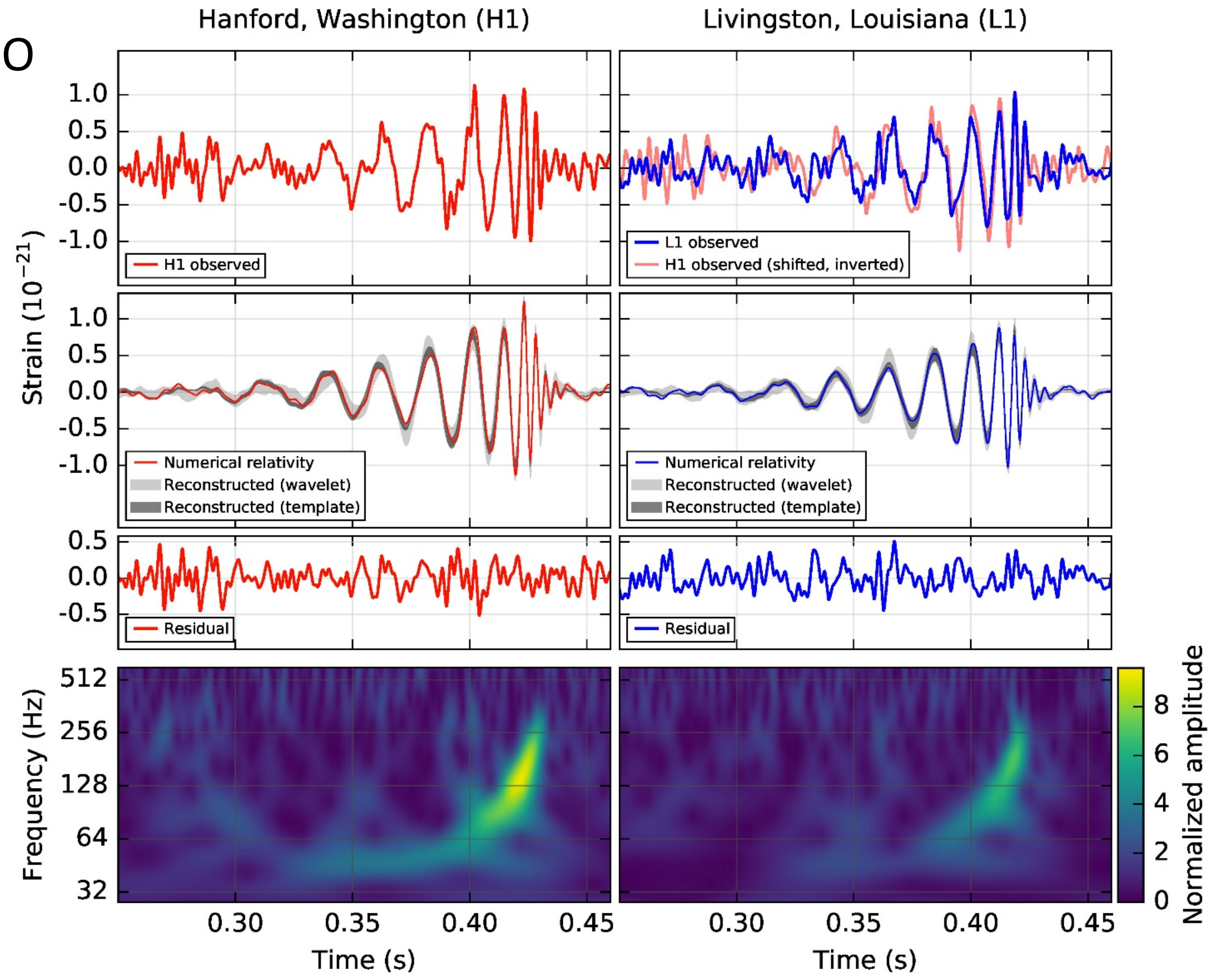
GW150914

Le 14 septembre 2015 à 09:50:45 UTC | 29 + 36 $M_\odot$

The observed signal

- Same signal in the 2 LIGO detectors, with a time difference = 7 ms
- Signal evolution = Typical signature of a coalescence
- Signal extracted from data matches the expected waveform for the coalescence of 2 black holes:

  36 et 29 solar masses



Signal validation

- Instrumental checks:
  - The 2 LIGO detectors operating normally at the time of the event
  - Quiet « weather » around the detectors
    - As usually meant + seismic, acoustic, magnetic…
    - Monitoring with array of sensors: ~ 100000 channels per detectors

- From data analysis:
  - Observed signal compared to expected signal for a coalescing binary system: → good matching
  - Estimate false alarm probability:
    - Probability that a random fluctuation, coincident in time in both detectors, produce a signal as intense as the one detected:

      p << 1 / 5 millions

Black holes

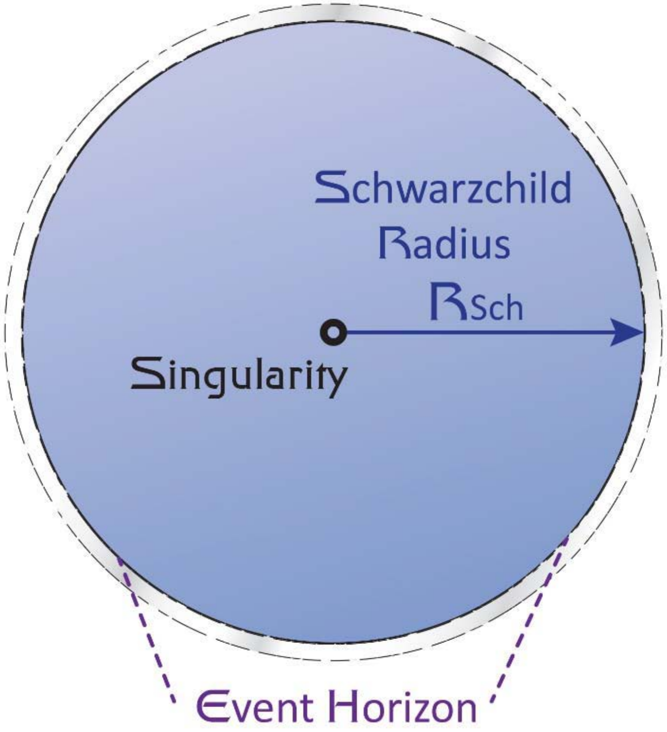
- The most compact stars
  - Matter condensed into a **singularity** at the center of the black hole
- Matter and light confined inside the **horizon**:
  - Schwarzschild radius:

$R_{Sch} = 2GM/c^2 = 3$ km for 1 M_{sun}

  - Classical computation :

escape velocity = c at the horizon

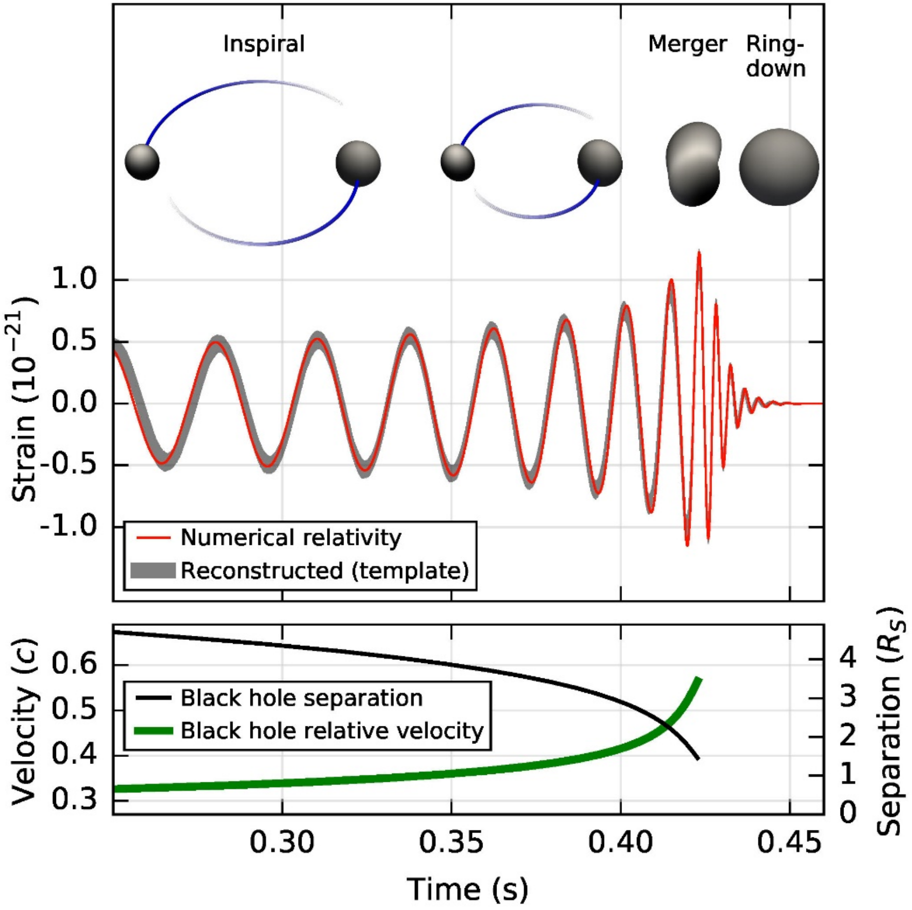
- Entirely described by 3 parameters:
  - Mass, kinetic momentum, electric charge



Why 2 black holes?

- ❑ Quantitative argument
  - ➢ Very good agreement between the observed signal and the theoretical waveform for the coalescence of 2 black holes

- ❑ Qualitatively:
  - ➢ Signal maximum at orbital frequency **75 Hz**
    - Separation **~ 350 km**
  - ➢ Signal evolution gives the mass of the system
    - Total mass > 70 $M_\odot$
    - Size of the black hole ($2R_S$) **~ 210 km**
    - Black hole compacity is required to reach 75 Hz without contact



Coalescence of the 2 black holes

Let’s go there!

A few impressive numbers

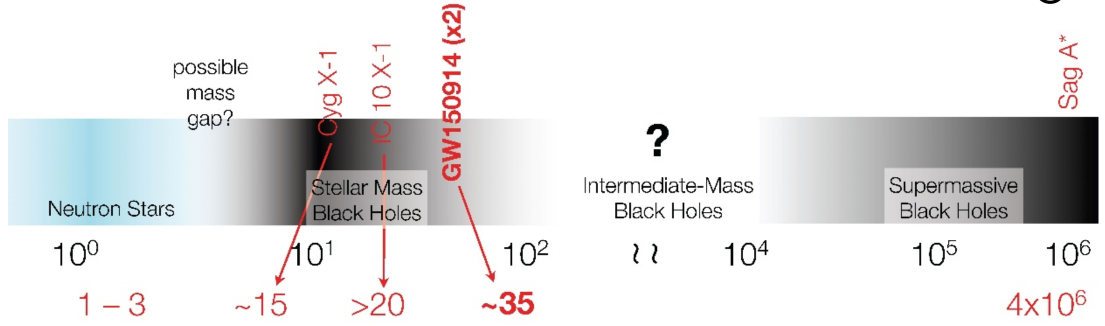
- Maximum amplitude of the signal: $h \sim 10^{-21}$
  - LIGO arm length has changed by $4 \, . \, 10^{-18}$ m
  - size of a proton / 250
- Distance to the source $D \sim$ 1.3 billion light-years
  - Waves emitted by the coalescence have travelled through space for ~ 1.3 billion yrs before crossing the Earth on Sep 14 2015
- Amount of energy radiated as GW by the binary system:

  $$E \sim 62 - (36 + 29) = 3 \ M_{\odot}$$

  - Most of it during the fraction of second preceding the merger
- Peak luminosity: $\mathcal{L} \sim 200 \ M_{\odot} / \mathrm{s}$
  - Briefly more powerful than all galaxies in the Universe

Astrophysical implications

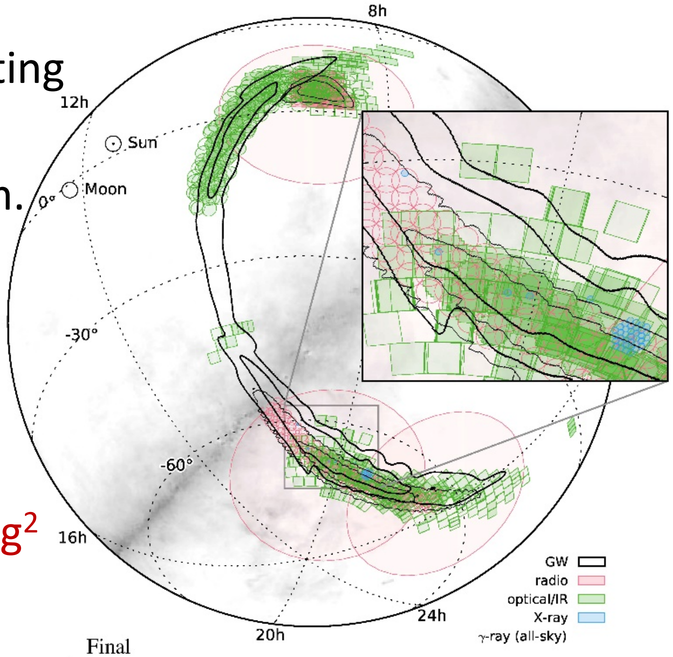
- First direct observation of black holes
- Relatively heavy stellar mass black holes exist in nature > 25 $M_\odot$
  - Implies low solar winds and low metallicity for the massive stars

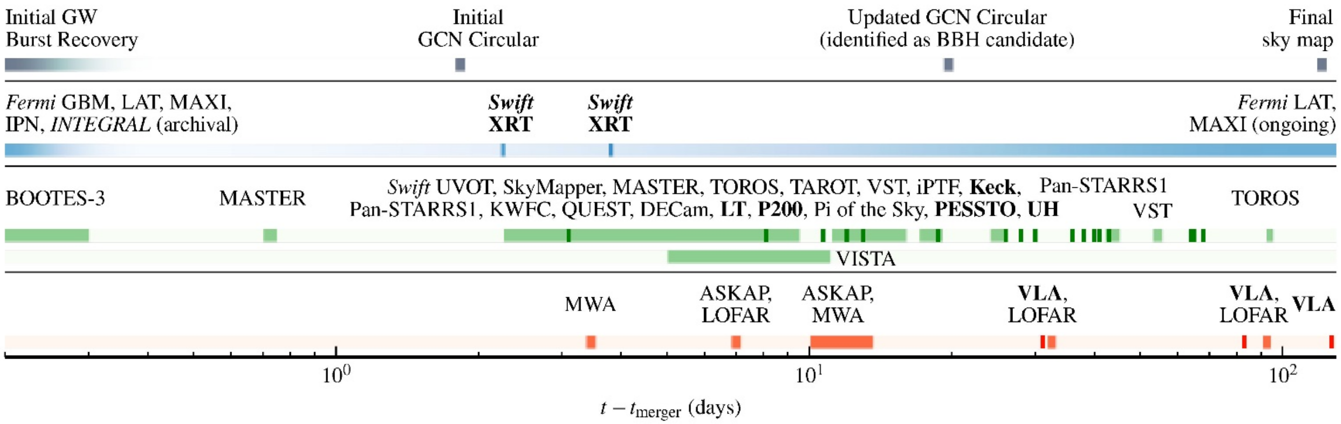


- Binary black holes form in nature
  - GW150914 does not allow to identify formation path
  - From isolated binary of massive stars vs dynamical capture in dense star clusters?
- Binary black holes merge within age of Universe
- These mergers happen at a rather high rate

Multi-messenger astronomy

- Agreement between LIGO, Virgo and partners from traditional astronomy
  - LIGO and Virgo share rapidly information about interesting events
  - 70 agreements signed, 160 instruments covering all e.m. spectrum from radio waves to high energy gamma rays
- 25 teams performed followup observations of GW150914
  - Looking for an electromagnetic counterpart
  - Difficult: probable area containing GW150914 $\sim$ 590 deg^2





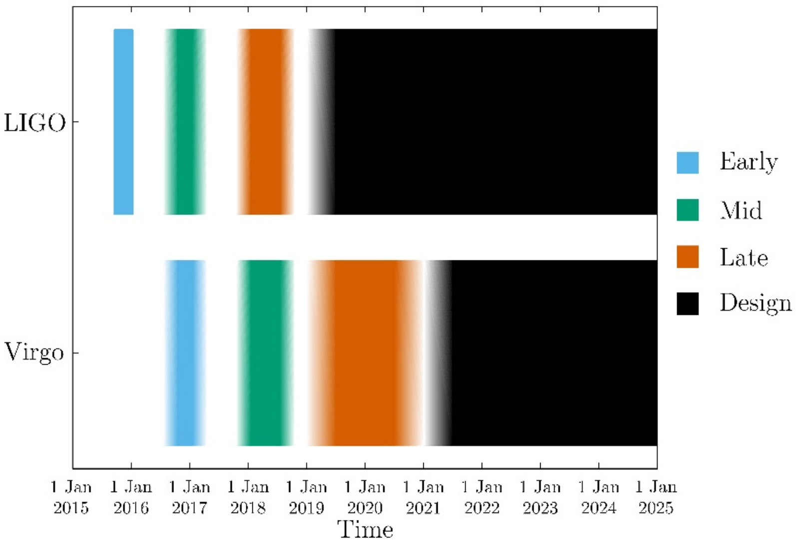
Probe gravitation under new conditions

- ❑ Orbital velocity in solar system ${}^{v}/_{c} \sim 10^{-5}$
- ❑ Most relativistic binary pulsar known today
  - ➢ J0737-3039, orbital velocity ${}^{v}/_{c} \sim 2 \times 10^{-3}$
- ❑ GW150914
  - ➢ Strong gravitational field, non linear effects, high velocity regime: ${}^{v}/_{c} \sim 0.5$
- ❑ Loudness of GW150914 already allows some coarse tests:
  - ➢ Does the observed signal correspond to GR predictions?

    Yes! (within the accuracy allowed with GW150914)
  - ➢ Bound on graviton mass

This is only the beginning

- GW150914 found after analyzing the first part of LIGO data-taking run O1 (Sep 15- Jan 16)
  - Full run analysis not yet completed
- Advanced Virgo will become operational in 2016
- Detector sensitivities will be improved, observation campaigns will become longer:
  - From the first detection to routine observations
  - … and the unexpected?



Conclusion

- ☐ GW150914 : first direct detection of gravitational waves, and first direct observation of a black hole binary
- ☐ An instrumental achievement
- ☐ A confirmation of General Relativity predictions, and a new tool for deeper tests of gravitation
- ☐ The beginning of a new scientific field:

  → gravitational-wave astronomy

Brief history of interferometric detectors

- ❑ 1st generation interferometric detectors
  - ➢ Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

- ◆ Enhanced LIGO, Virgo+

Improved sensitivity

Lay ground for multi-messenger astronomy

- ❑ 2nd generation detectors

First detection

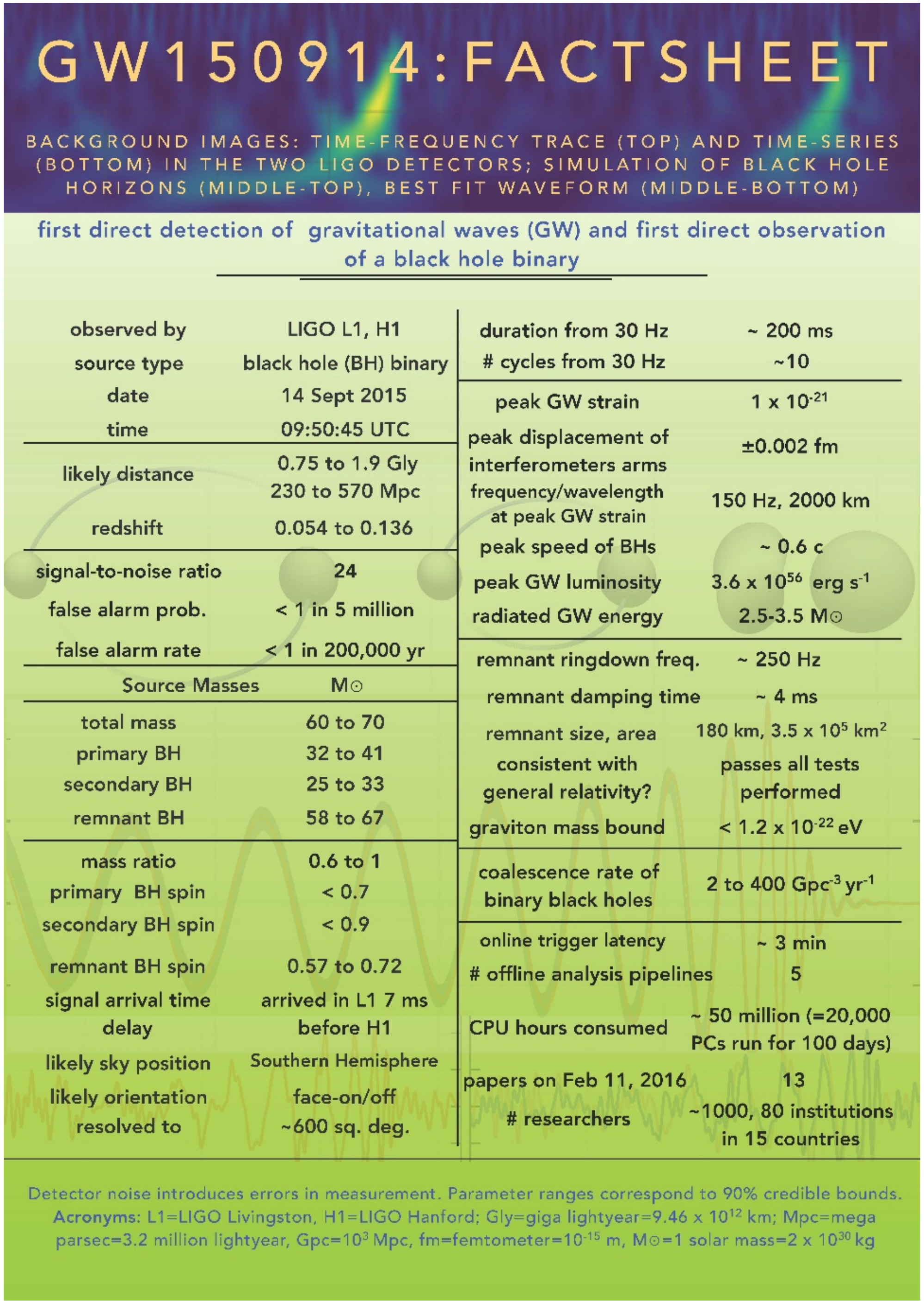
- ◆ Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA

Towards routine observation

➔ GW astronomy

- ❑ 3rd generation detectors
  - ◆ Einstein Telescope, Cosmic Explorer

Thorough observation of Universe with GW



GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^{5} km^{2}
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46 x 10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^{3} Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2 x 10^{30} kg