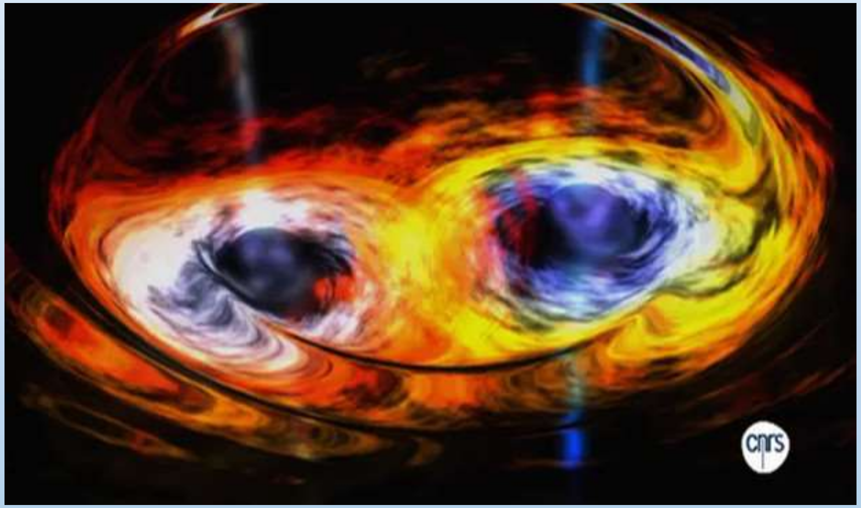
Gravitational waves

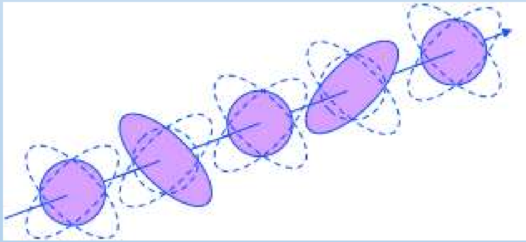


Pierre Gruning, LAL-CNRS | French-Ukrainian workshop 6-8th November 2017

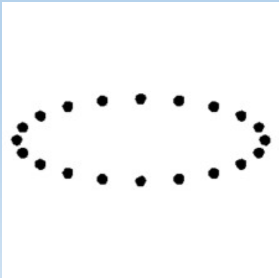
LIGO
LAL LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
VIRGO

What are Gravitational waves ?

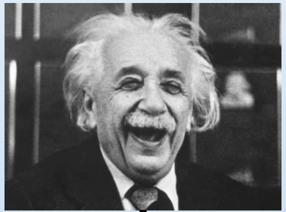
- Solution from General Relativity derived by A. Einstein in 1916, first experiments in the 60s
- Gravitation is a curvature of the space-time metric
- Any massive object will introduce a deformation of the metric
- Far from sources they can be seen as a perturbation of the metrics ie :
  - They are ripples of space-time produced by rapidly accelerating mass distributions
  - Provide info on mass displacement
  - Weakly coupled – access to very dense part of objects



- Main proprieties:
  - Propagate at speed of light
  - Two polarizations ‘+’ and ‘x’
  - Produce a differential effect on metric
  - Emission is quadrupolar at lowest order
  - Need compact and relativistic objects



Gravitational waves : a brief history

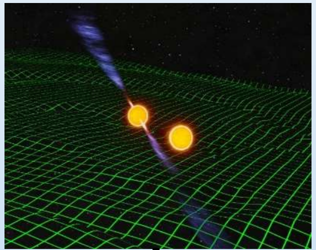


1918

A. Einstein
Über Gravitationswellen

First attempt : Weber bars

1968

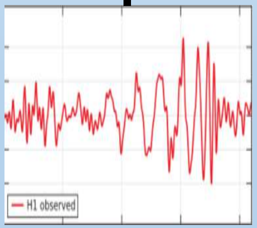


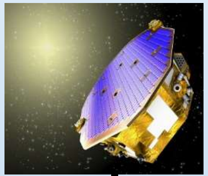
1974

First indirect detection :
Hulse-Taylor Pulsar
(Nobel prize)

First direct detection !

14th September 2015





3rd December 2015

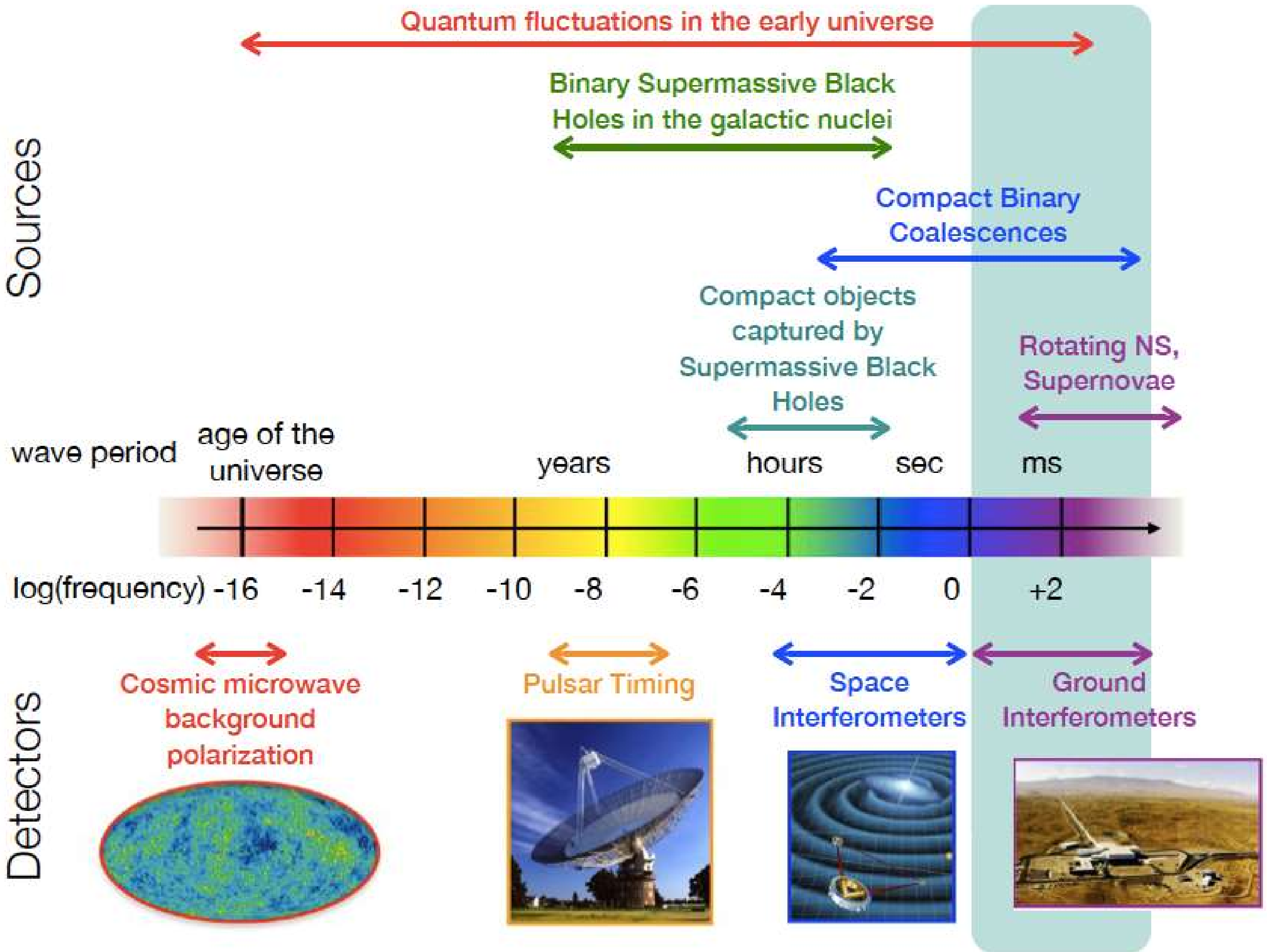
Launch of LISA Pathfinder

- First 3 detector detection
- First observation of binary NS
- First EM counterpart
- Nobel prize

2017

eLISA
2034 ?

The Gravitational Wave Spectrum



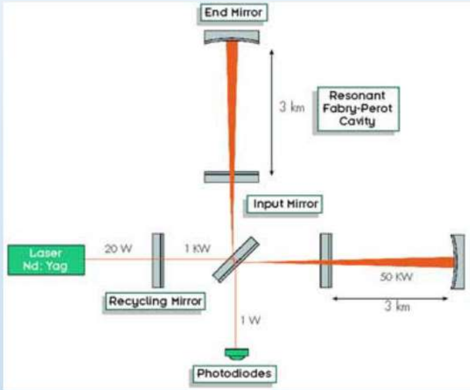
[Inspired from http://science.gsfc.nasa.gov/663/research/]

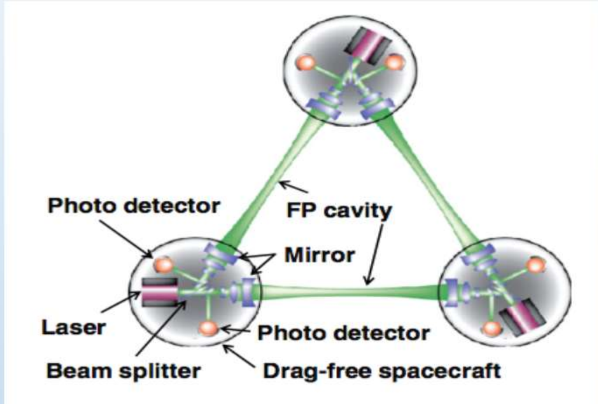
How can we detect them ?

5 types of experiments to detect GW :

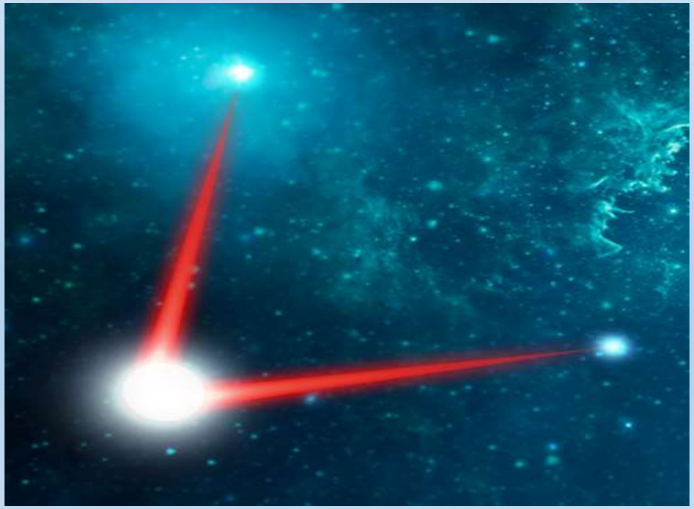
- Looking at B-modes in the CMB (Cosmic Microwave Background)
- PTA (Pulsar Timing Array)
- Measuring orbital period of binary pulsars
- Resonant bars
- Laser interferometry

How can we detect them ?

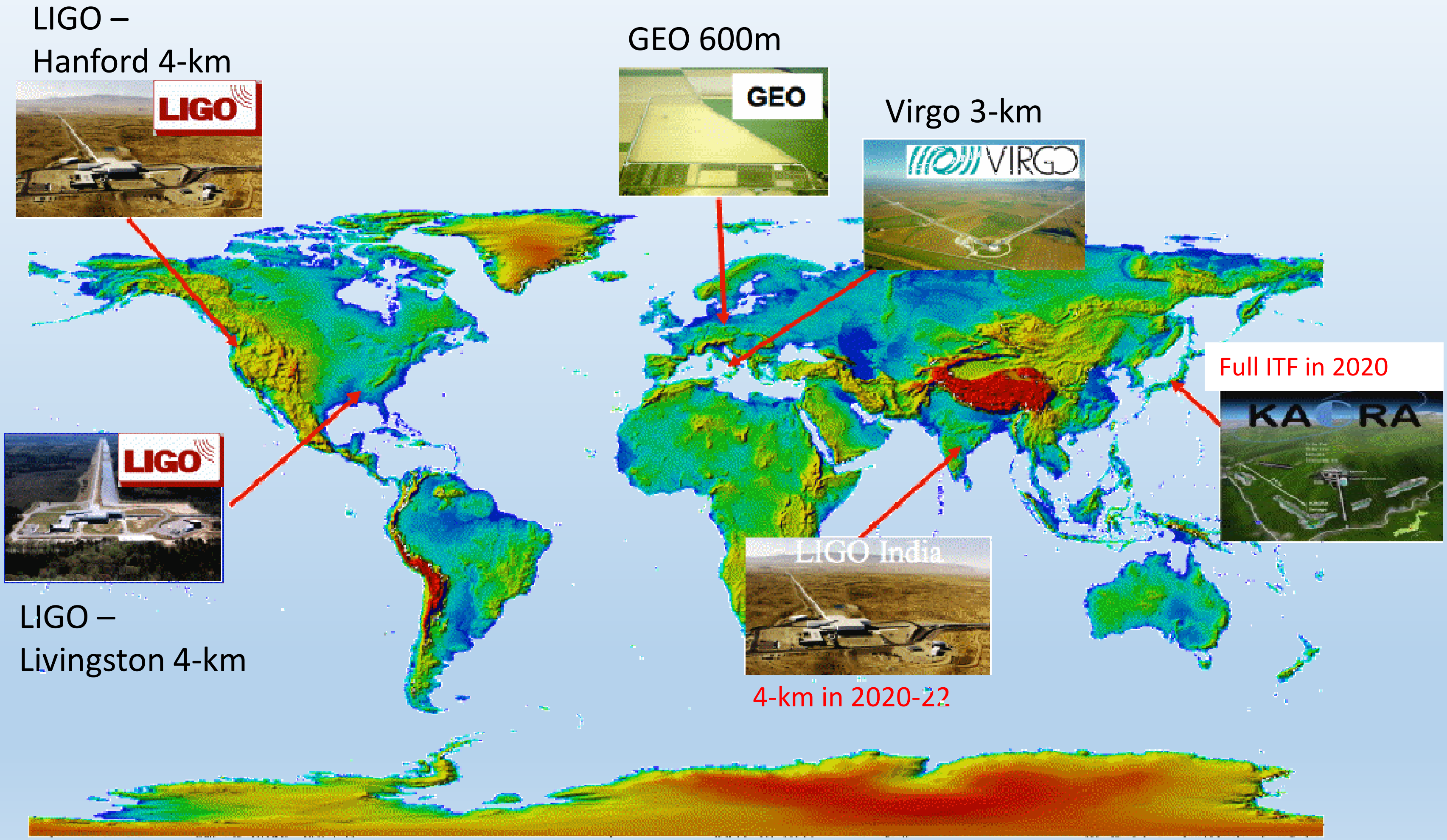




Laser interferometry

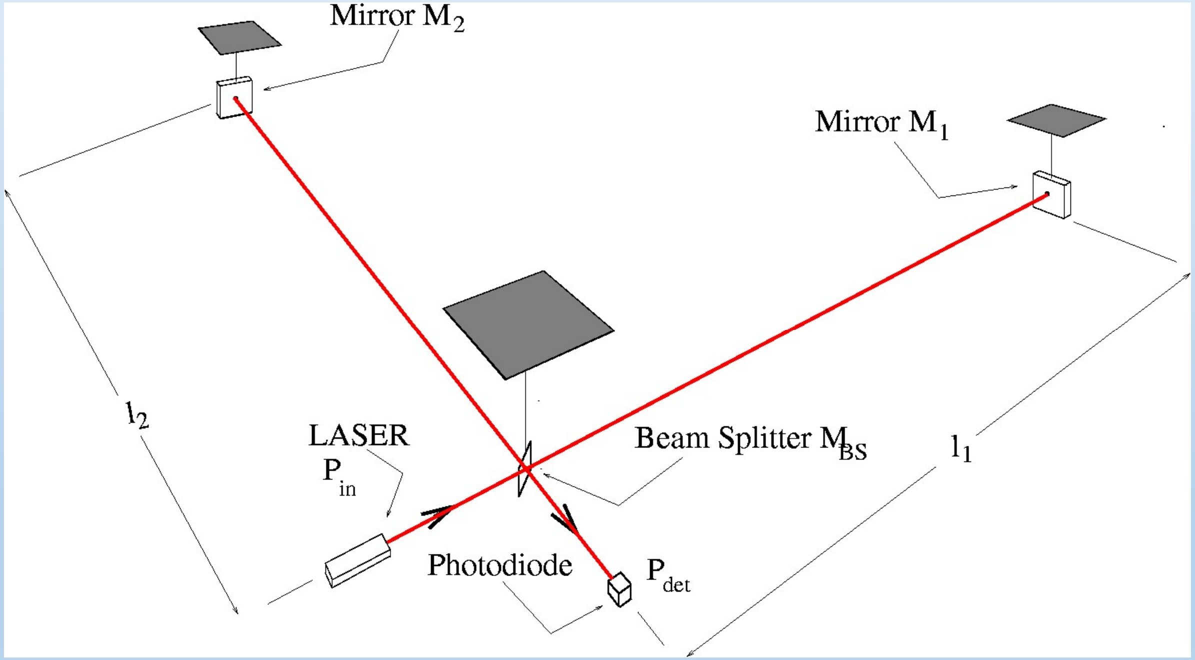


The GW detectors networks



LIGO/Virgo type interferometers

- Mirrors act as test masses of the metric
- Using differential effect -> variation of detected light at ouput ports



$$P_{\text{det}} = \frac{P_{in}}{2}\left(1 + C\cos(\Delta\phi)\right)$$

$$C = \frac{2 r_1 r_2}{r_1^2 + r_2^2}$$

$$\Delta\phi = \underbrace{\frac{2\pi(l_2 - l_1)}{\lambda}}_{\equiv \Delta\phi_{OP}} + \underbrace{\frac{2\pi(l_2 + l_1)h(t)}{\lambda}}_{\equiv \delta\phi_{GW}}$$

$$P_{\text{det}} = \frac{P_{in}}{2}\left(1 + C\cos(\Delta\phi_{OP}) - C\sin(\Delta\phi_{OP}) \times \delta\phi_{GW}(t)\right)$$

Advanced generation !

Michelson interferometer

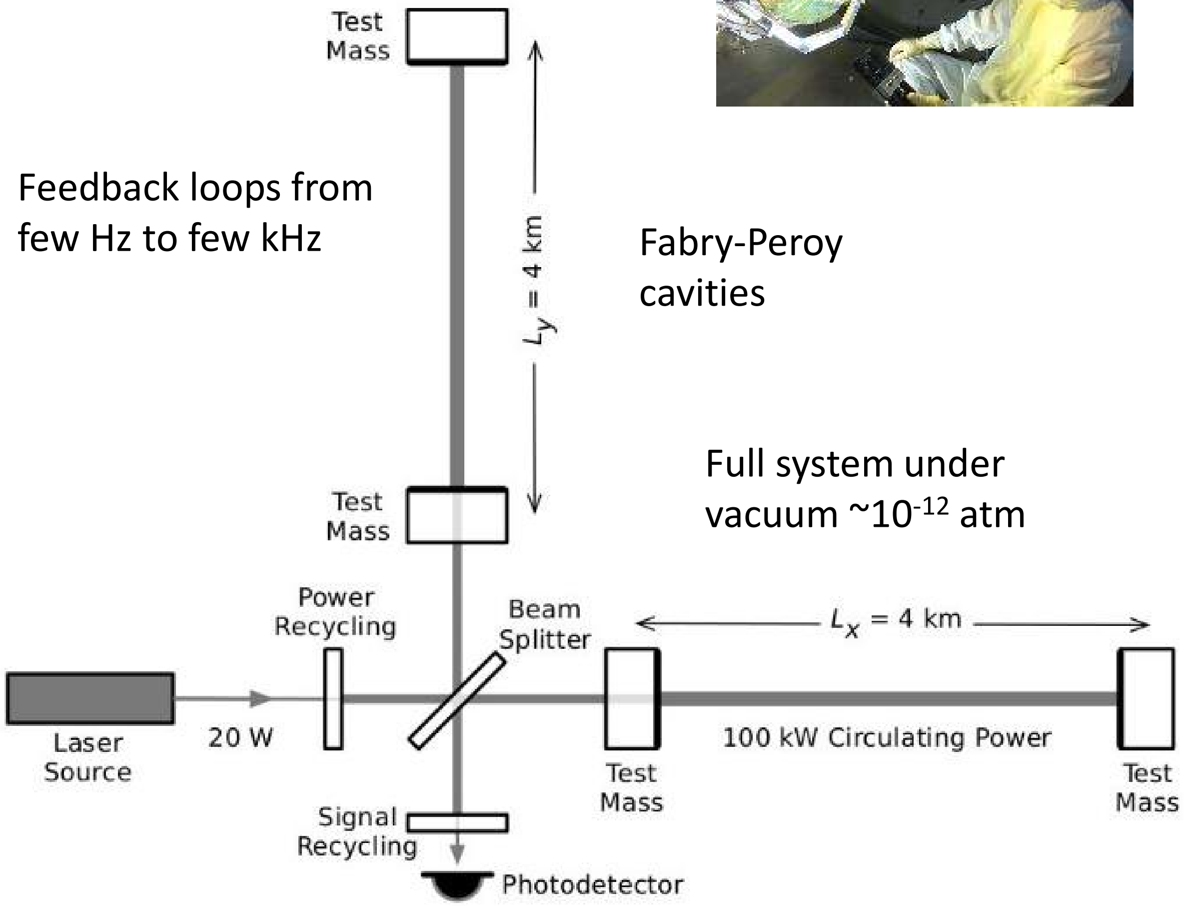
Goal : $(L_x-L_y)/L_x = 10^{-23}$

High quality optics – 40 kg

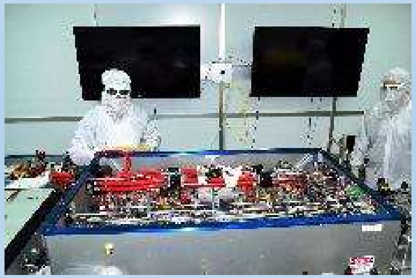
Feedback loops from few Hz to few kHz

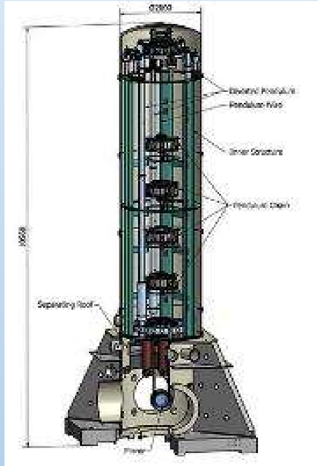
Fabry-Peroy cavities

Full system under vacuum ~10^{-12} atm



High power laser

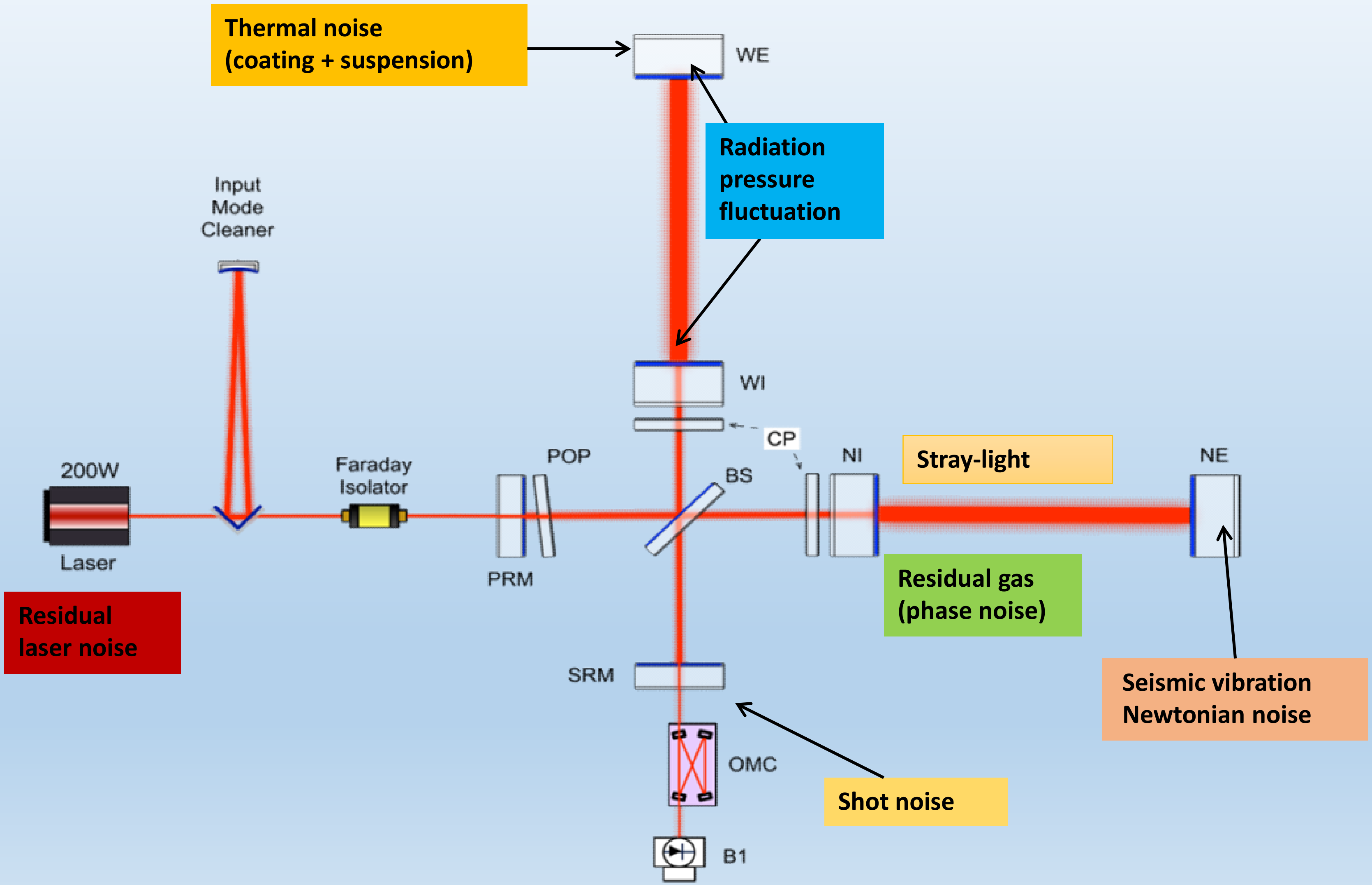




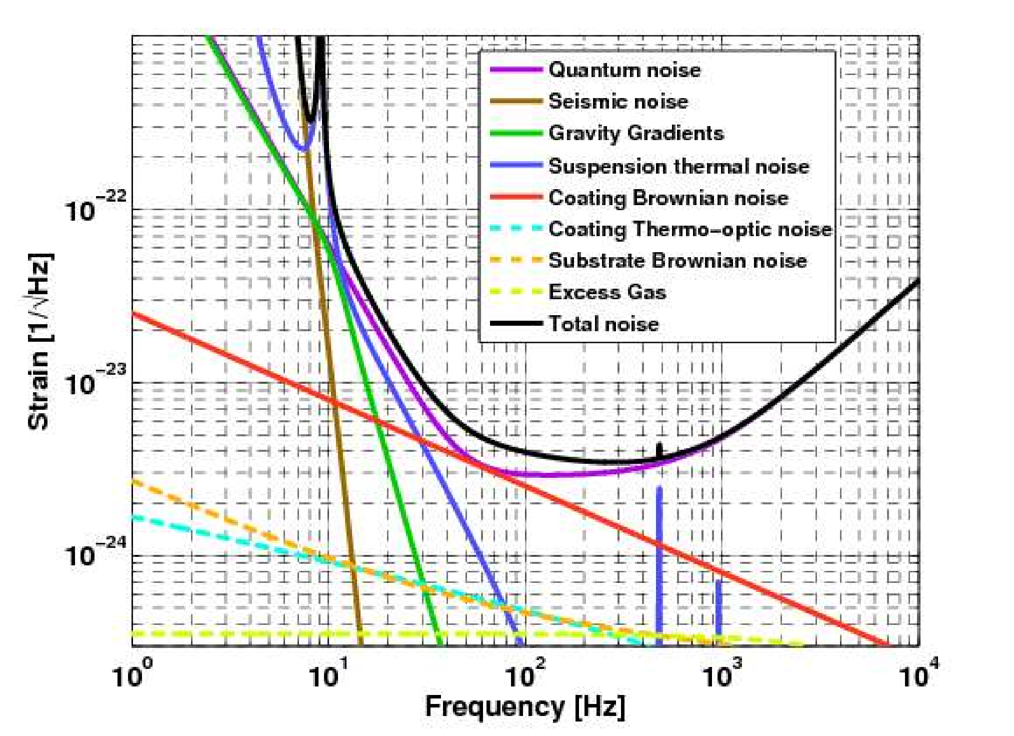
Suspended Optics

Attenuation 10^{14} @ 10 Hz

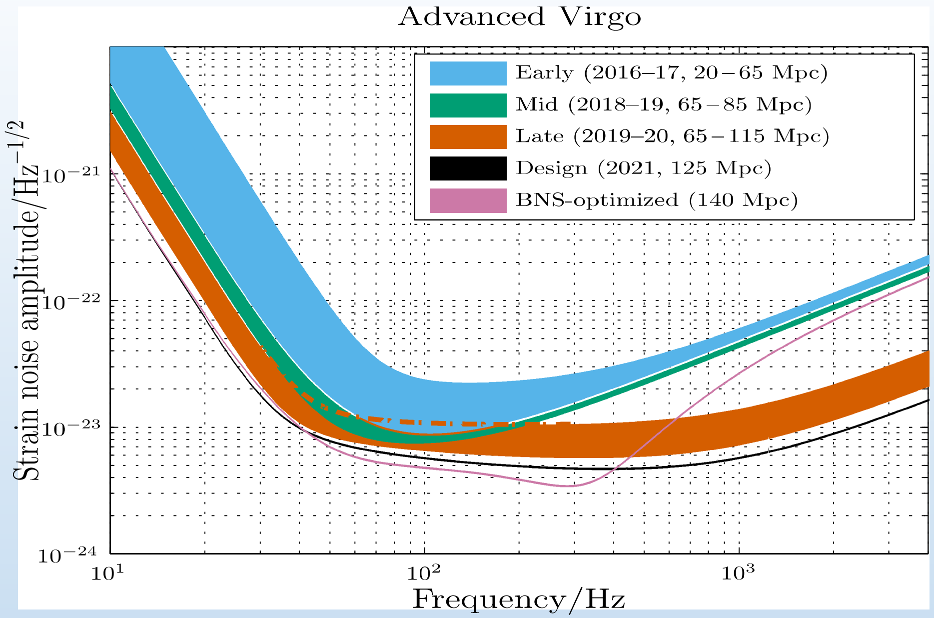
Main sources of noise

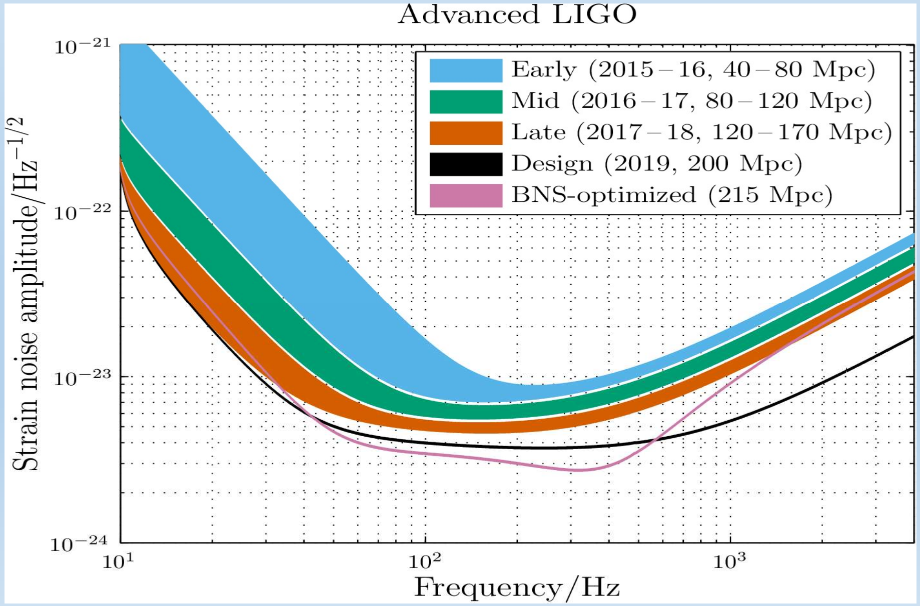


LIGO/Virgo sensitivity



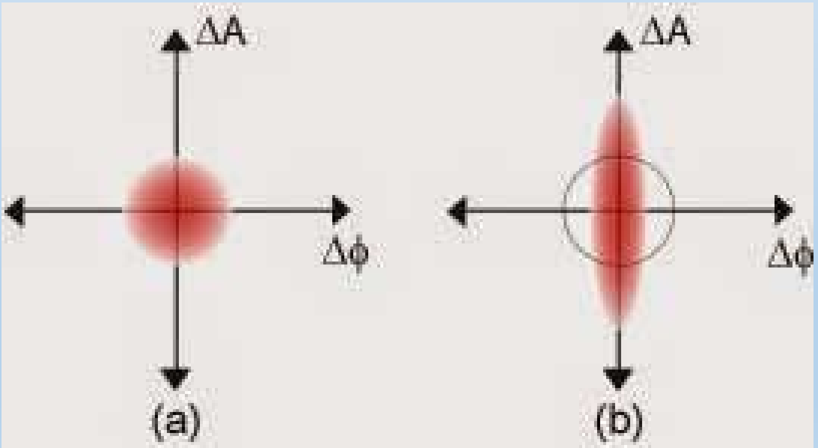
AdLIGO design sensitivity

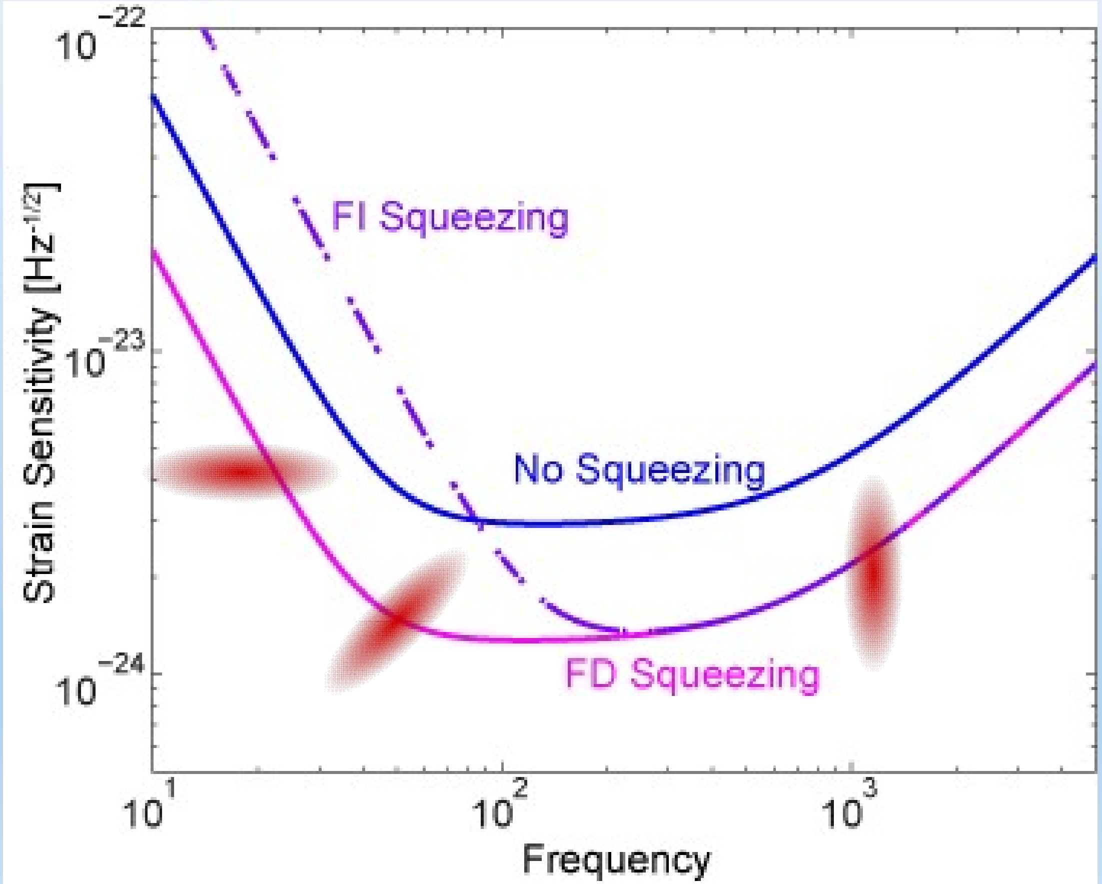




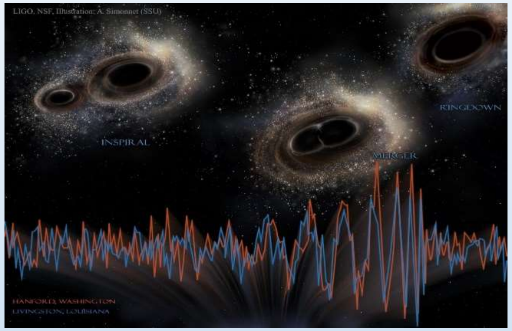
Ongoing work to increase sensibility, next step : beat standard quantum limit using squeezed light

Frequency-dependent Squeezing used to simultaneously squeeze both radiation pressure and shot noise at different frequency regions where they dominate

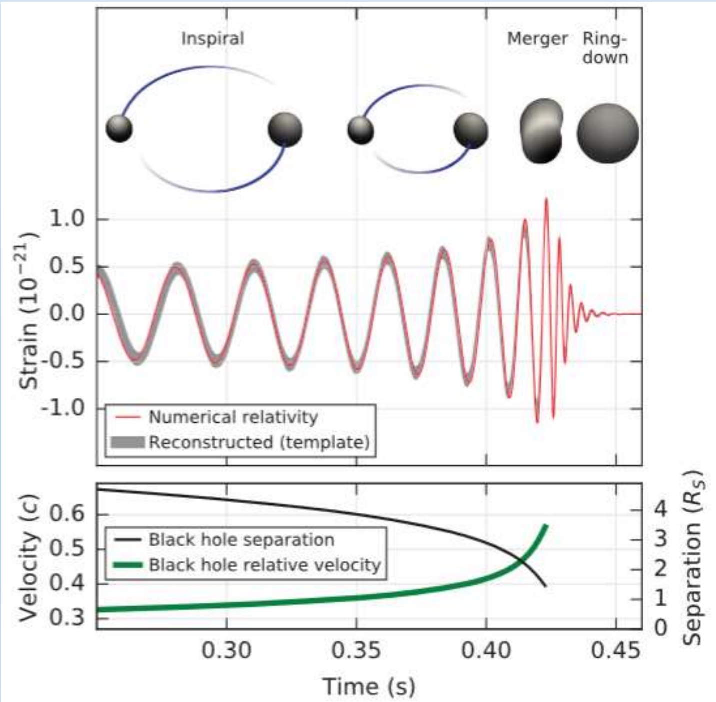




14th september 2015 : First direct detection of gravitational waves



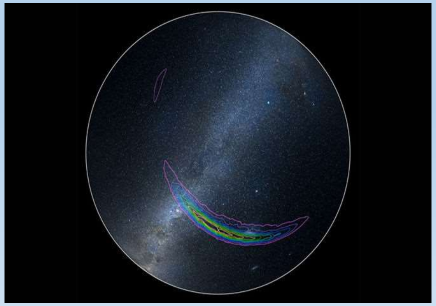
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal.



LIGO has seen the merging of 2 stellar black holes that occured 1,3 billion years ago :

- Merger of 2 black holes of 36 and 29 solar masses
- Final black hole of 62 solar masses
- Energy equivalent of 3 solar masses radiated in gravitational waves
- Source distance : 410 MPc = $1{,}3.10^{25}$ m = $1{,}3.10^{9}$ Ly

To compare, the diameter of our galaxy is ≈ 100 000 Ly



But with only 2 detectors the event is localized in an area of 600 deg²

But since then new detections were made :

GW150914 : first direction detection of gravitational waves (BBH)

GW151226 : second detection from (BBH) → LIGO

GW170104 : third detection from (BBH)

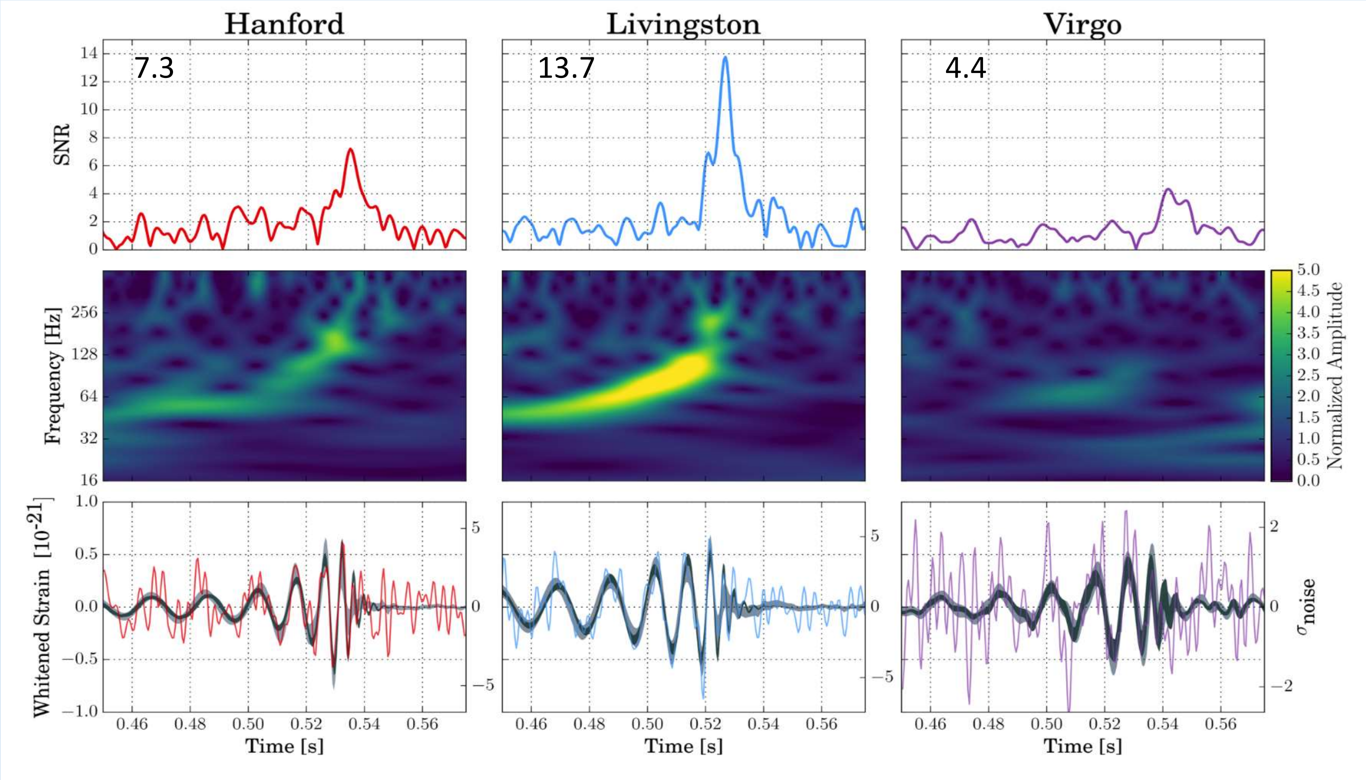
GW170814 : first 3 detector detection (BBH)

GW170817 : first 3 detector detection of a BNS merger

→ LIGO + Virgo

GW170814 : Virgo first detection

- Signal arrived at on August 14, 2017 10:30:43 UTC at Livingston, 8 ms later at Hanford, 14 ms later at Virgo;



Random chance to have signal in Virgo

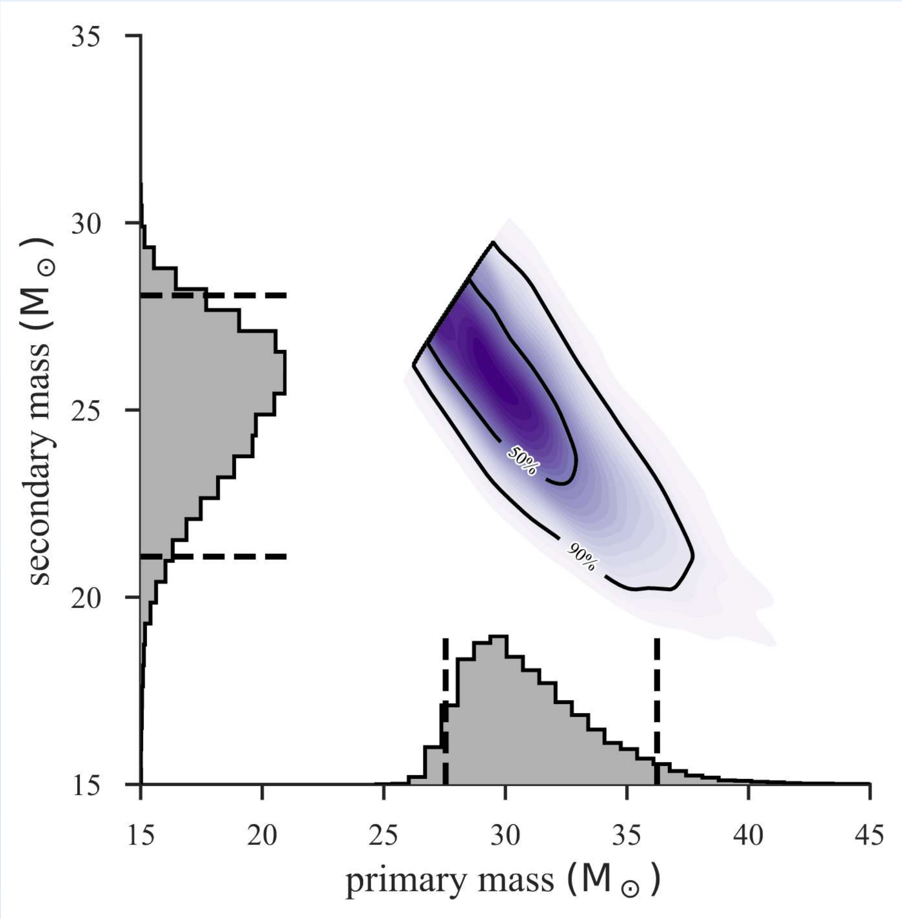
< 0.3 %

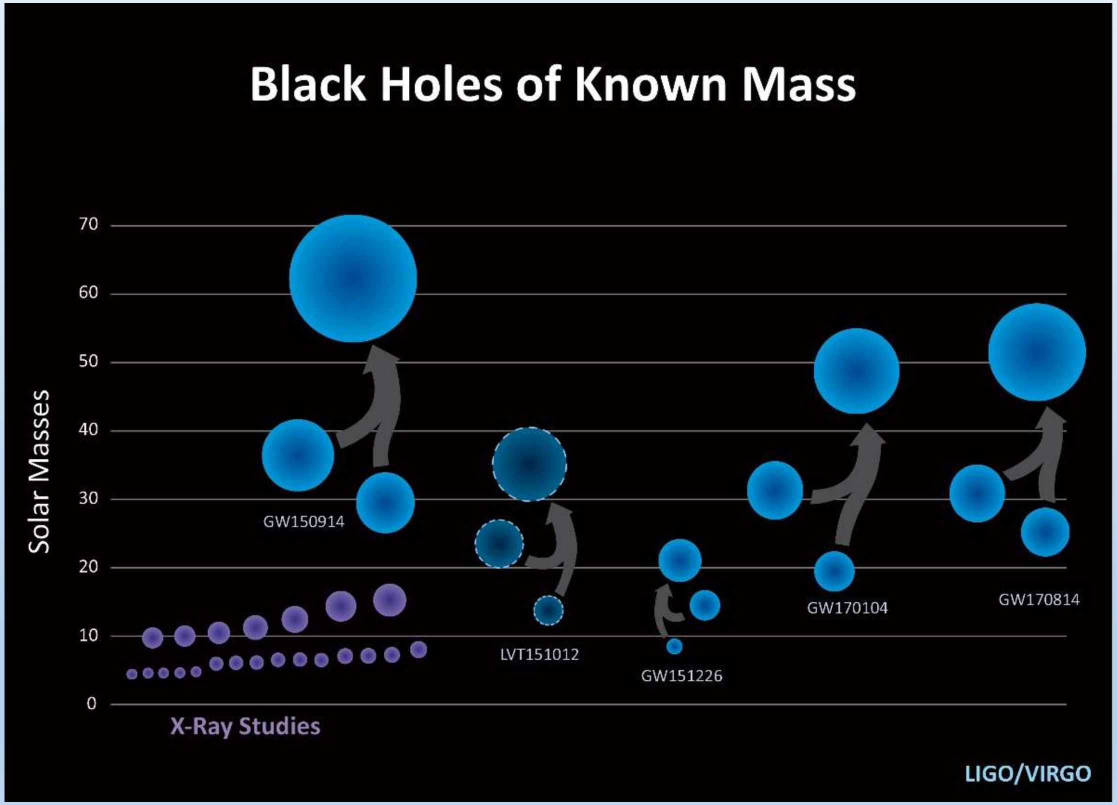
false alarm rate

< 1 in140,000 years

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, Abbott *et al.* , PRL 119, 141101

A new binary black holes





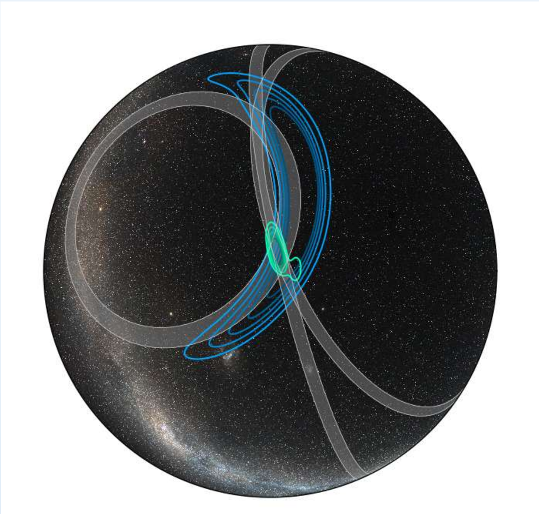
GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, Abbott *et al.* , PRL 119, 141101

Source parameters

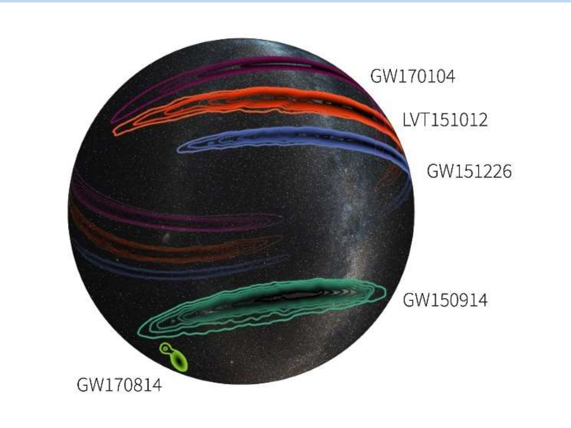
Primary black hole mass m_1	$30.5^{+5.7}_{-3.0}\ \mathrm{M}_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2}\ \mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}\ \mathrm{M}_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}\ \mathrm{M}_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5}\ \mathrm{M}_\odot$
Radiated energy E_rad	$2.7^{+0.4}_{-0.3}\ \mathrm{M}_\odot \mathrm{c}^2$
Peak luminosity ℓ_peak	$3.7^{+0.5}_{-0.5} \times 10^{56}\ \mathrm{erg\,s}^{-1}$
Effective inspiral spin parameter χ_eff	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	$540^{+130}_{-210}\ \mathrm{Mpc}$
Source redshift z	$0.11^{+0.03}_{-0.04}$

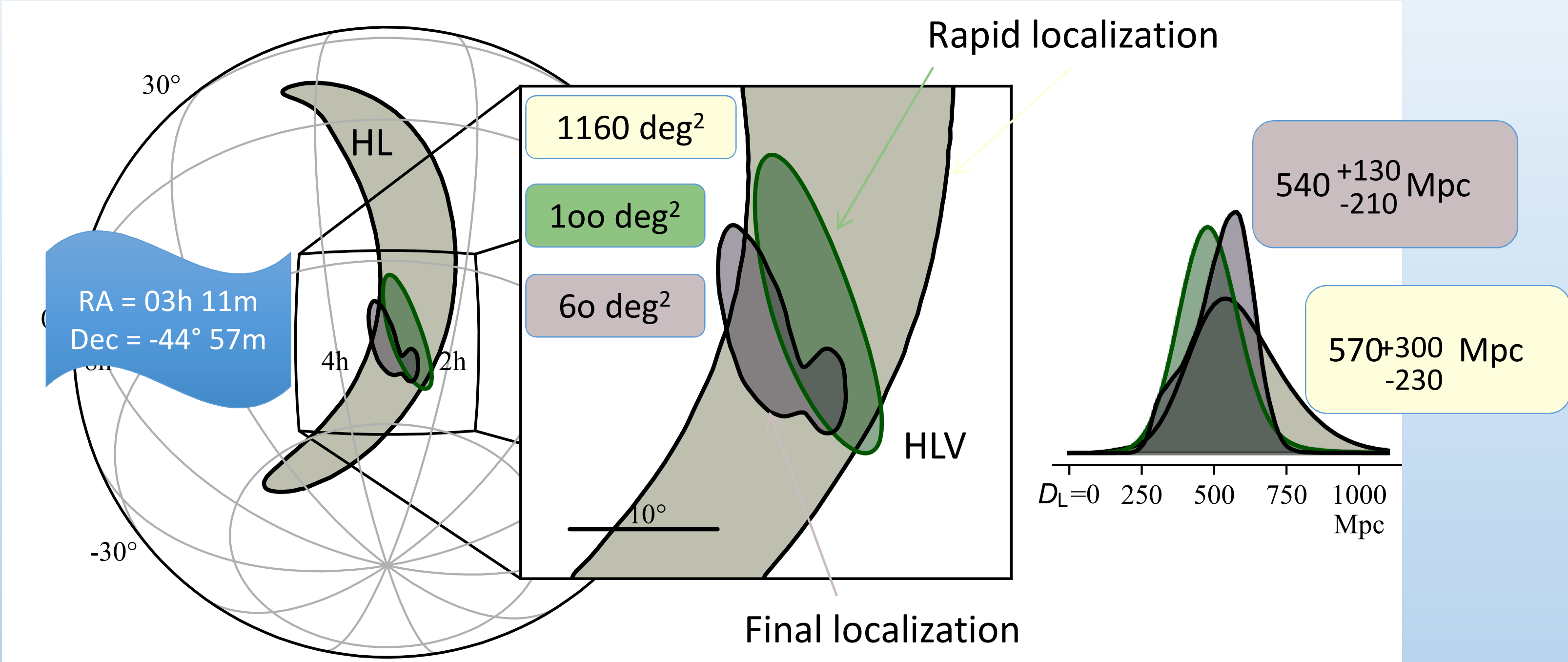
Chirp mass : $M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\ \pi^{-\frac{8}{3}} f^{-\frac{11}{3}} \dot{f}\right]^{3/5}$

Better sky localisation



Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)





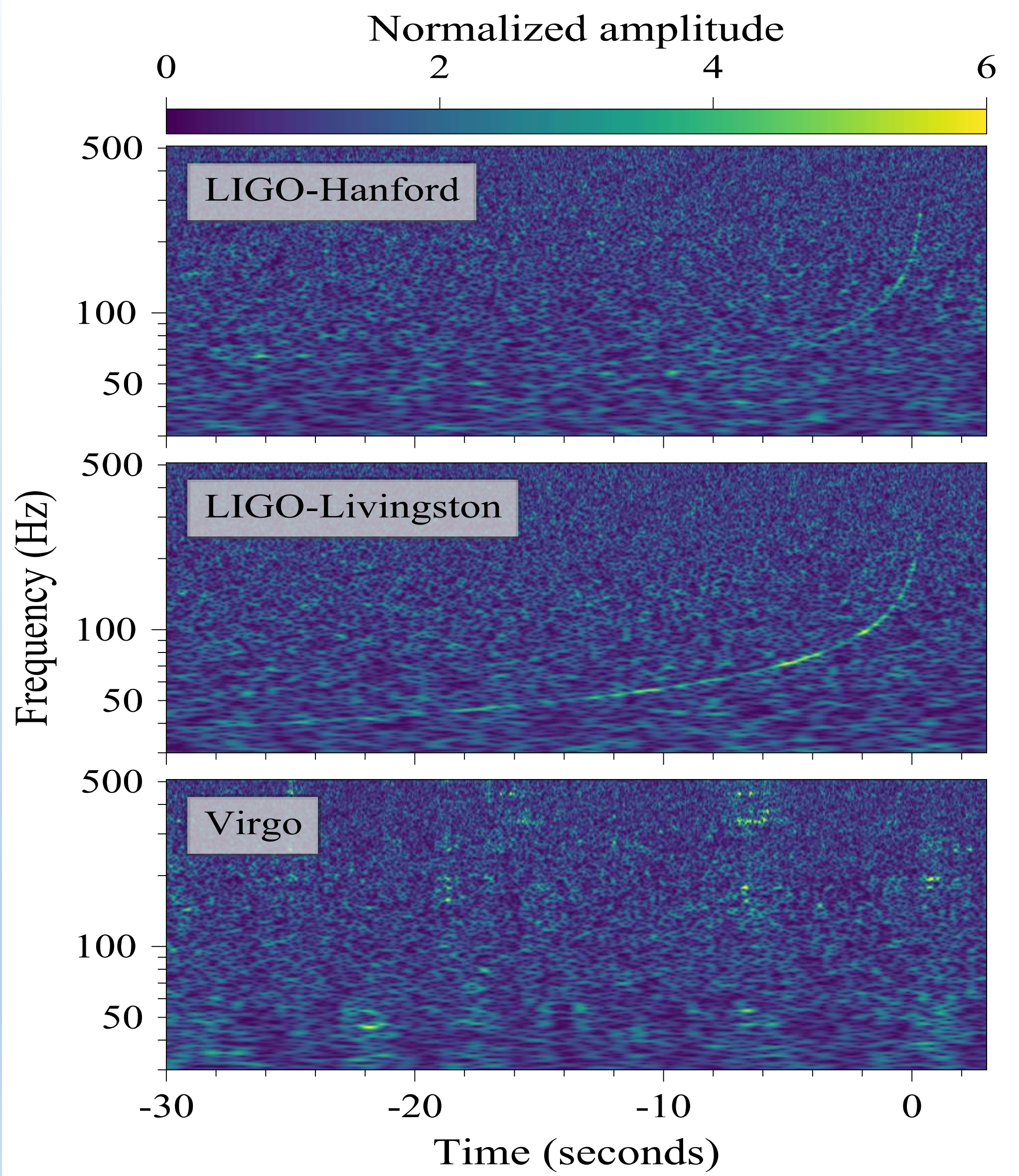
Error in sky area : factor 20 !

Reduced incertitude in distance by 1.5

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, Abbott *et al.* , PRL 119, 141101

3 days later …

- SNR ~ 32.4, FAR ~ $1 10^{-6}$ year $^{-1}$
- Long event (~100 secs) can be seen in the data, light masses system !
- Probability to have at least one neutron star is important
- Possible electromagnetic counterpart !
- Already a possible association with a gamma ray-burst



Source parameters

Using LIGO+Virgo data

	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	$1.36 - 1.60\,M_\odot$	$1.36 - 2.26\,M_\odot$
Secondary mass m_2	$1.17 - 1.36\,M_\odot$	$0.86 - 1.36\,M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002}\,M_\odot$	$1.188^{+0.004}_{-0.002}\,M_\odot$
Mass ratio m_2/m_1	$0.7 - 1.0$	$0.4 - 1.0$
Total mass m_{tot}	$2.74^{+0.04}_{-0.01}\,\mathrm{M}_\odot$	$2.82^{+0.47}_{-0.09}\,\mathrm{M}_\odot$
Radiated energy E_{rad}	$> 0.025\,\mathrm{M}_\odot\,\mathrm{c}^2$	$> 0.025\,\mathrm{M}_\odot\,\mathrm{c}^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Misalignment of total angular momentum and line of sight	$\leq 56°$	$\leq 55°$
using counterpart location	$\leq 30°$	$\leq 30°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	≤ 800	≤ 1400

What an alert !

17/08/2017 12:41:04 — Signal from BNS : GW170817

+2 s — Detection from Fermi/GBM of a short gamma-ray burst (GRB170817A)

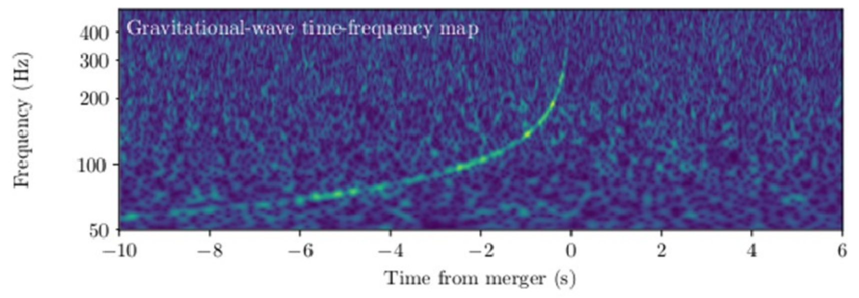
+16 s — GRB alert sent

+40 min — Sent alert on GW side

BEGINNING OF THE MULTI-MESSENGER CAMPAIGN

+1h20min — First reports from temporal coincidences with GW170817

Report from Integral/SPI-ACS Detected GRB170817A



« Gravitational waves and Gamma-rays from binary neutron star merger: GW170817 and GRB170817A », Abbott et al., ApJ, 2017

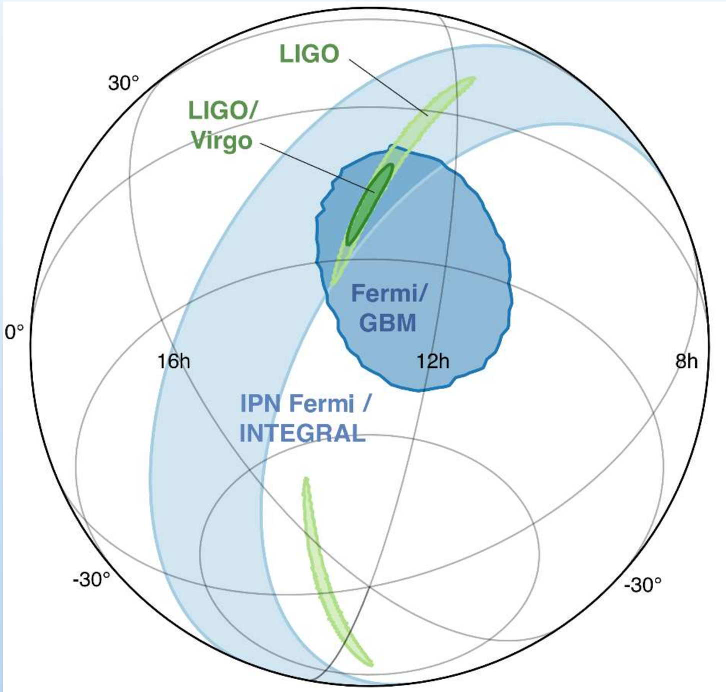
P(GW-GRB only by chance) < $5\ 10^{-8}$

Key role from Virgo in the localisation

17/08/2017
12:41:04 — GW170817

+5h — GW : send updated skymap with the 3 detectors

+10h — GW : send updated skymap with refined algorithm



« Multi-messenger observations of a binary neutron star merger », Abbott et al., ApJ, 2017

GW170817 localization	
2 interferometers (HL)	AddingVirgo (HLV)
190 deg^2, distance 40 Mpc	28 deg^2, distance 40 Mpc Volume : 380 Mpc^3

Less than 100 galaxies could be the host of the event !!

17/08/2017
12:41:04 — GW170817

+2 s — GRB170817A

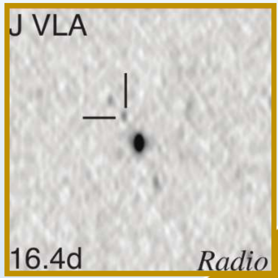
+5h — Localisation with GW
Distance 40 Mpc

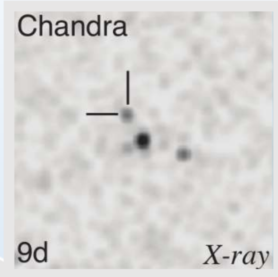
+11h — Discovery of kilonova AT2017gfo by Swope
Find host galaxy : NGC4993
START CAMPAIGN ON AT2017GFO

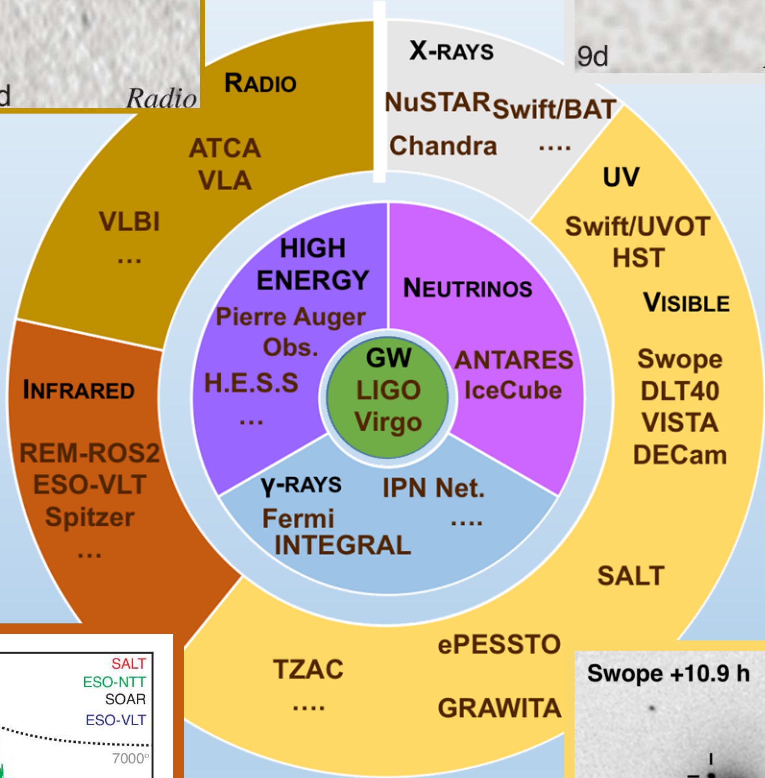
+1.2j — First spectra of the kilonova

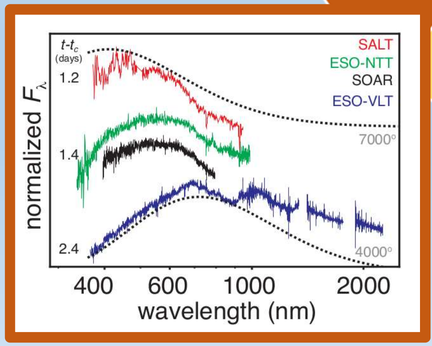
+9j — Discovery of an X-ray counterpart

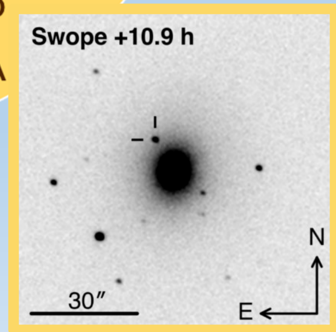
+16j — First radio signal found with VLA





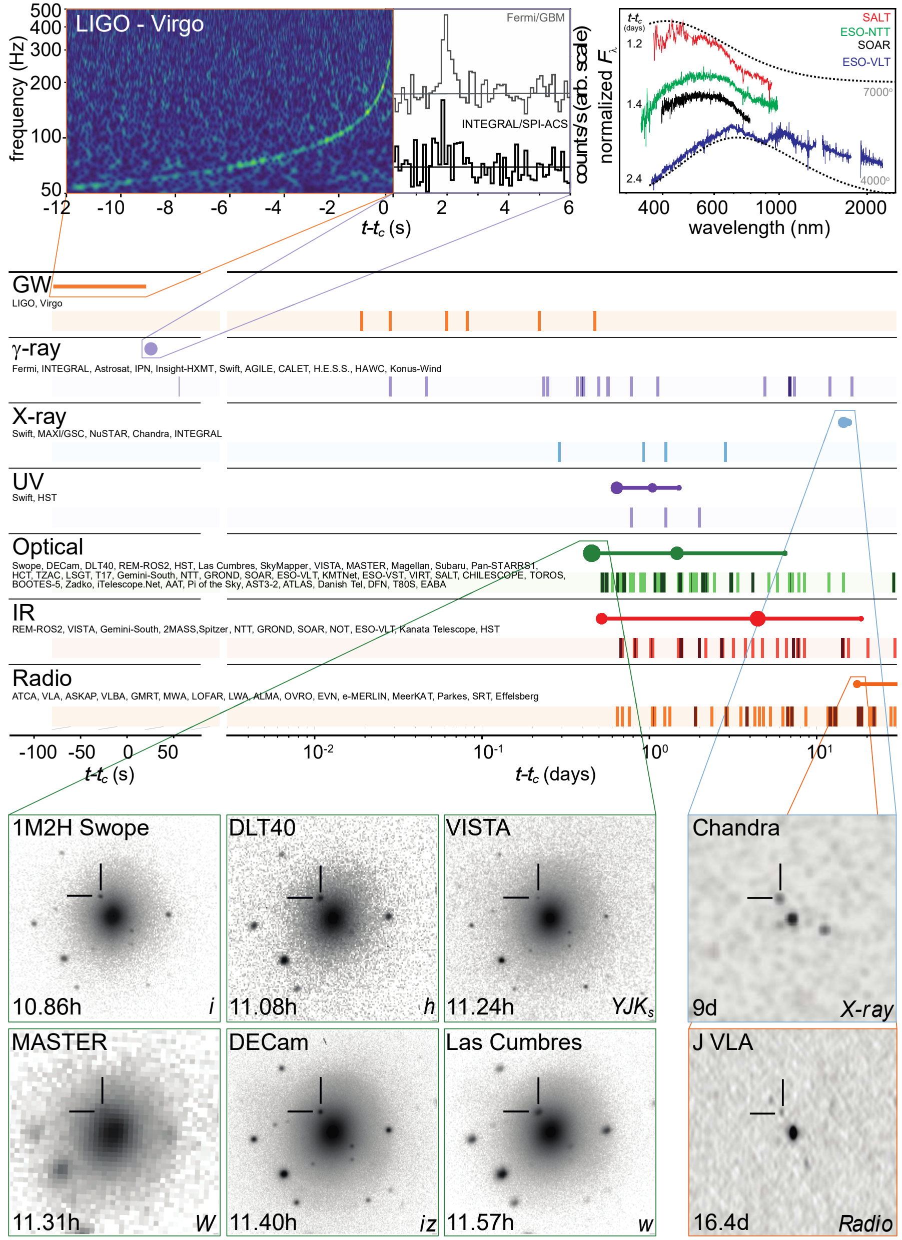






« Multi-messenger observations of a binary neutron star merger », Abbott et al., ApJ, 2017

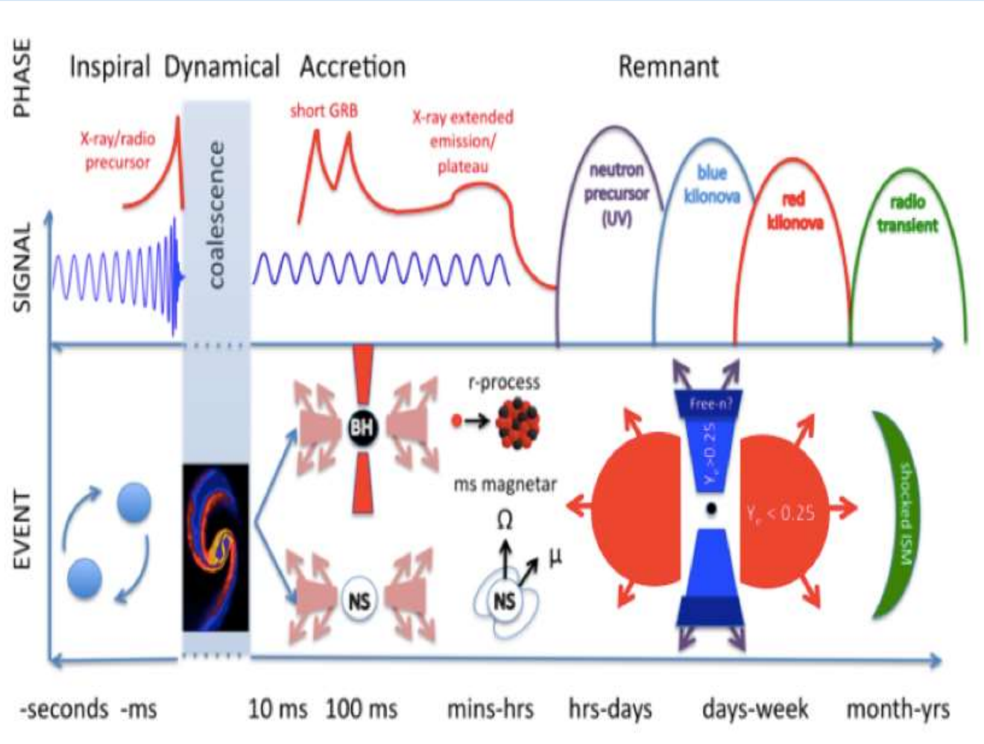
The full campaign (up to now)



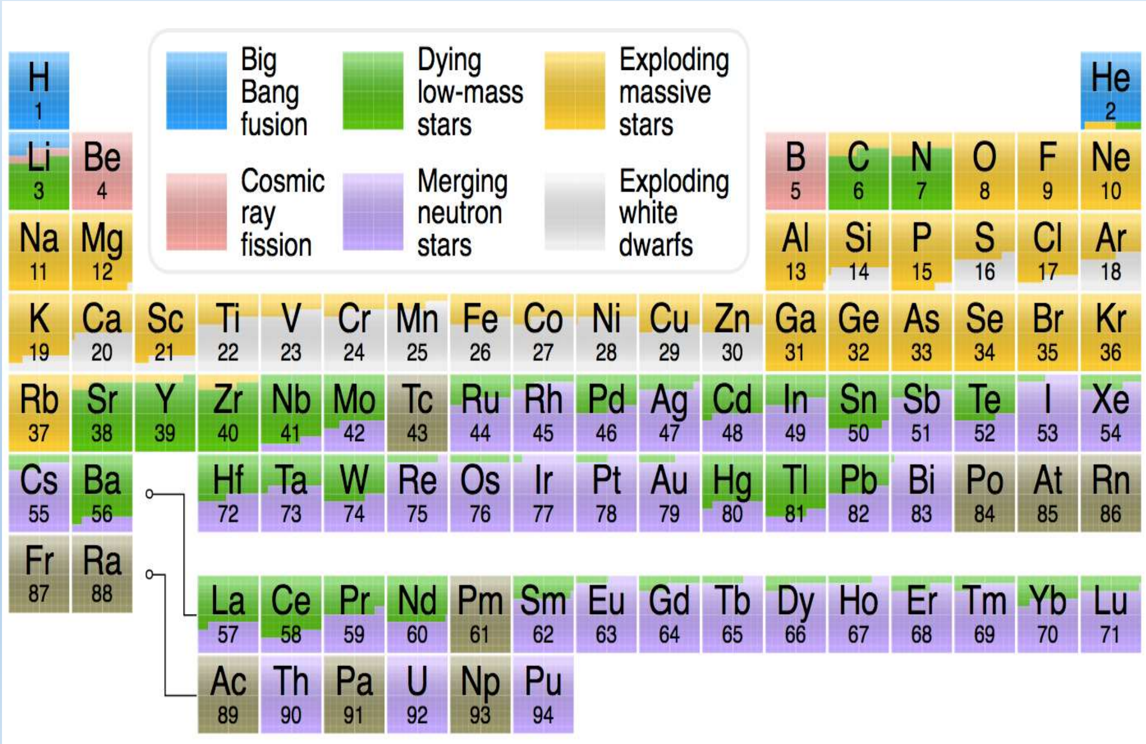
« Multi-messenger observations of a binary neutron star merger », Abbott et al., ApJ, 2017

Kilonova

- During merger phase rich neutrons matter could produce heavy elements by neutron capture (r-process)
- Quasi isotrope emission, heated by radioactivity, emission expected to shift from blue to red during cooling



Fernandez and Metzger, A.. Rev. Nuc. Part. Sci. 2016, 66



Main results with GW170817

- GW170817 is the closest (and loudest) GW event ever observed
- First binary neutron stars system detected with GW
- Having three detectors allow to have a quite good localization and allow a full observation campaign
- Confirmed that this BNS is the central engine of a short GRBs – association with GRB170817A > 5.3 σ
- Complete multi-messenger follow-up campaign confirm also association with a kilonova
- Start to put some constraints on EOS
- Test of fundamental physics can also be performed
- A first H_0 independent measurement

Common GW-GRB analysis

Test for fundamental physics using time delay and source distance

- Speed of gravity : $$-3.10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq +7.10^{-16}$$

- Equivalent principle (Shapiro effect) :

$$\delta t_S = -\frac{1+\gamma}{c^3} \int_{r_e}^{r_o} U(r(l))\, dl$$

gravitational potential

$$-2.6\,10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2\,10^{-6}$$

Deviation to Einstein-Maxwell

- Lorentz Invariance violation :

Improve between a factor 2 and 10 previous constraints

"Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A", ApJL in press (2017)

Conclusion

The field of gravitational is very active:

- First detection of black holes
- Discovery of a new population of binary black holes
- First detection of a neutron star binary in GW domain
- First EM counterpart
- Detector network is growing, on earth, soon in space
- Improvements are ongoing