Astronomie des ondes gravitationnelles :

Détections avec le réseau LIGO-Virgo et 70 observatoires (de la radio au TeV)

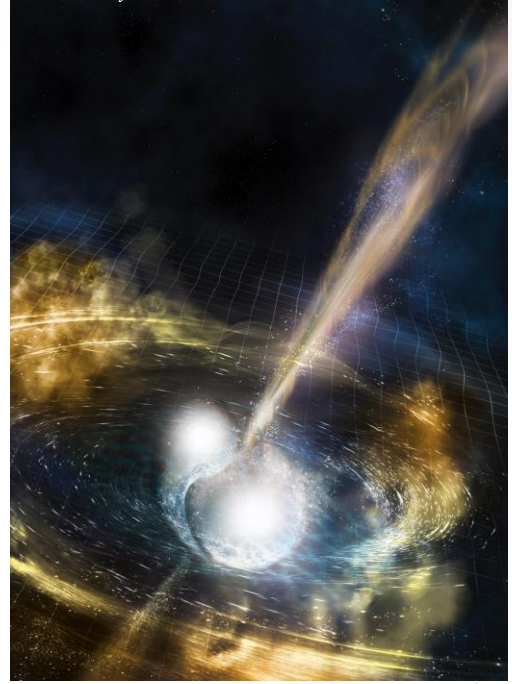
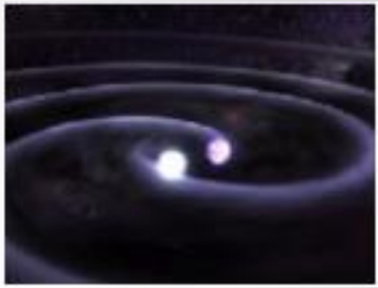


Image Credit: LSC/Sonoma State University/Aurore Simonnet

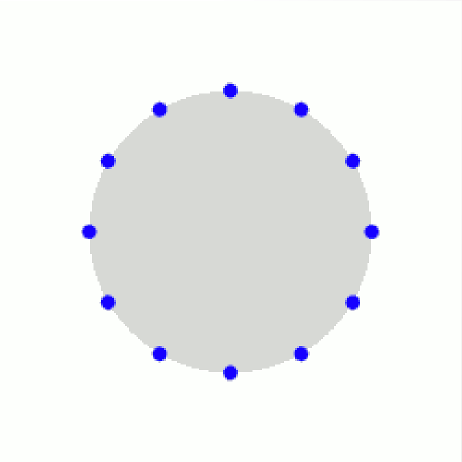
Nicolas Leroy
Laboratoire de l'accélérateur linéaire

23 juillet 2018

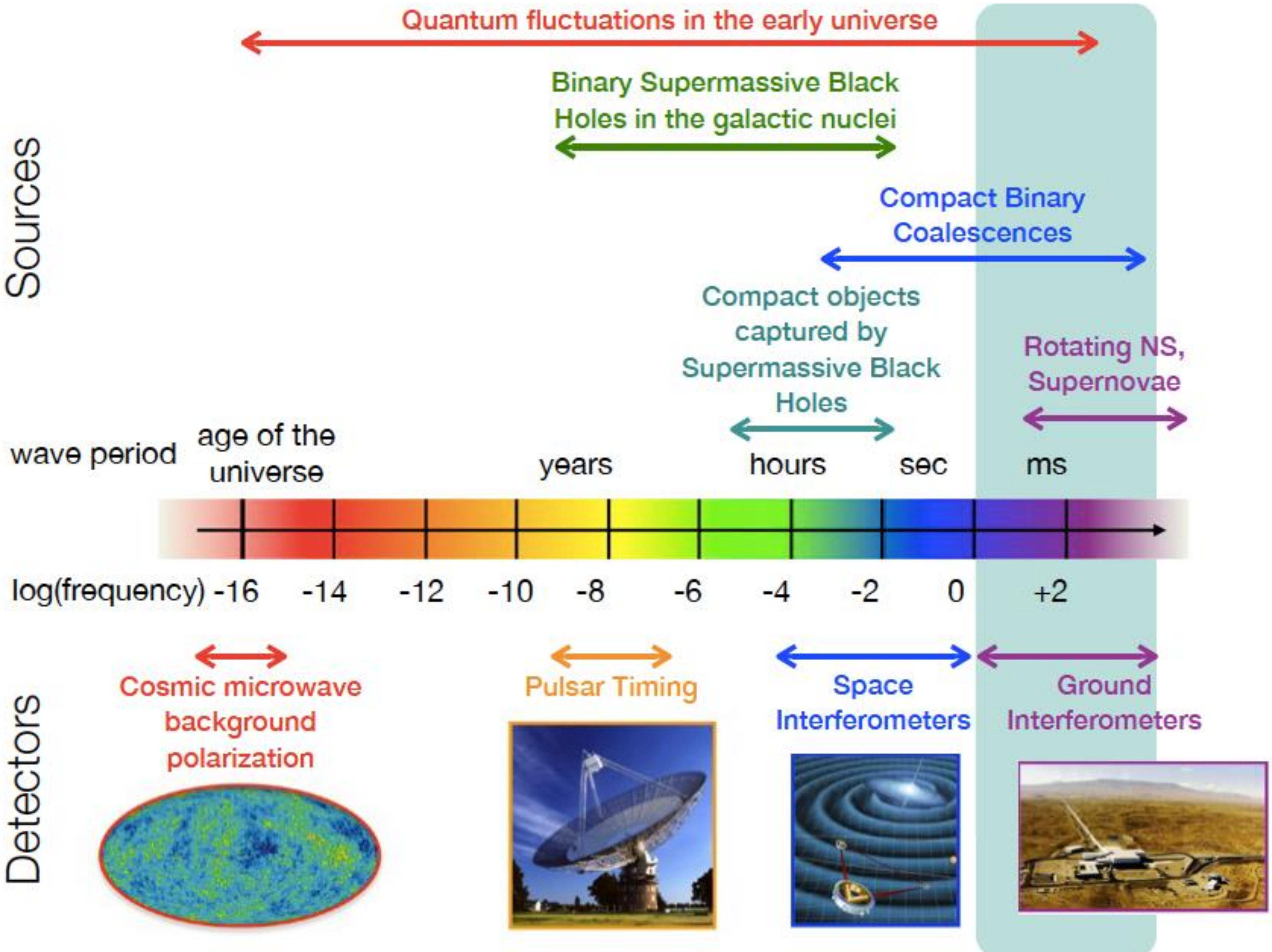
What are Gravitational waves ?



- Solution from General Relativity derived by A. Einstein in 1916
- 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



The Gravitational Wave Spectrum

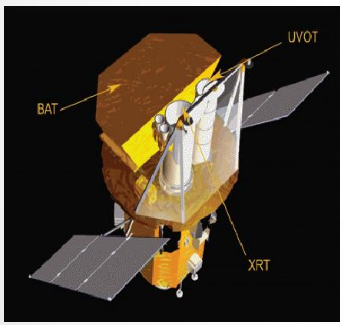


[Inspired from http://science.gsfc.nasa.gov/663/research/]

Multimessenger astronomy

Gamma-rays

X-rays



Optical

GRB

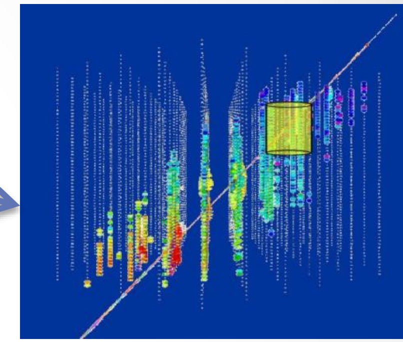
SGR/AXP

Supernovae
type II

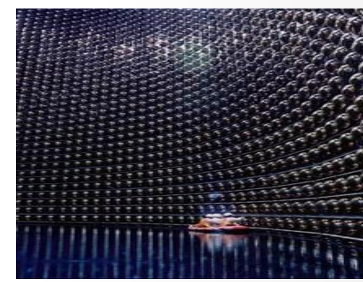
Giant Flare

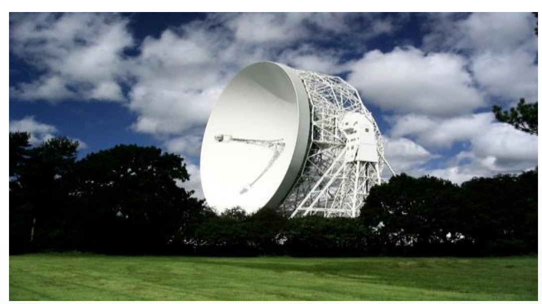
Pulsar/
pulsar glitches

HE (>1 TeV) ν



LE (MeV) ν

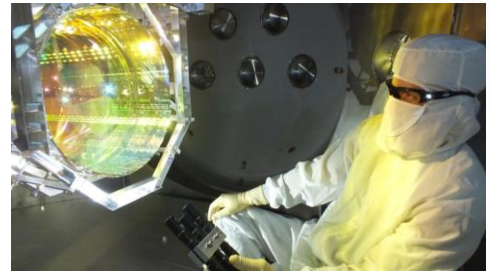




Radio

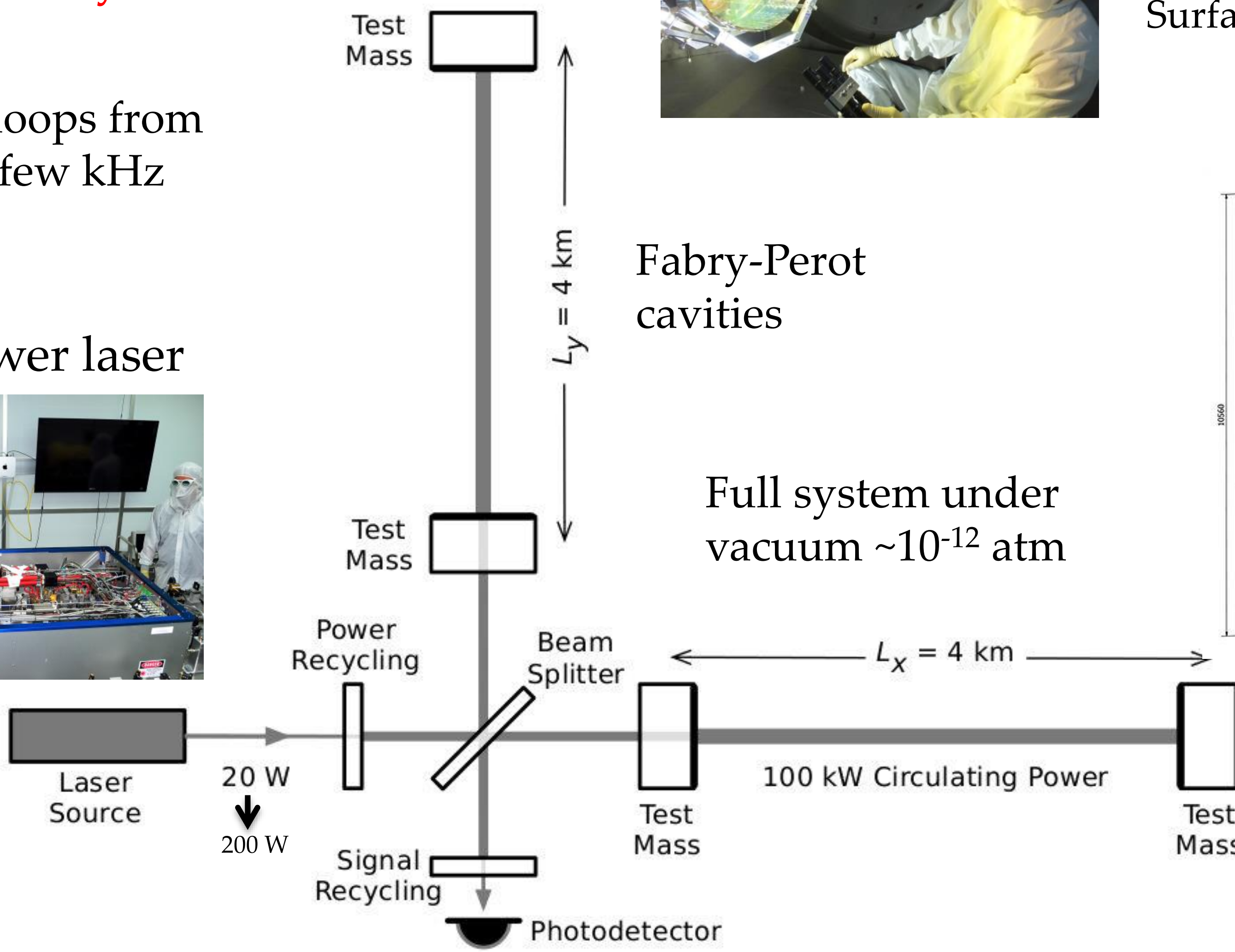
Advanced generation detectors

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



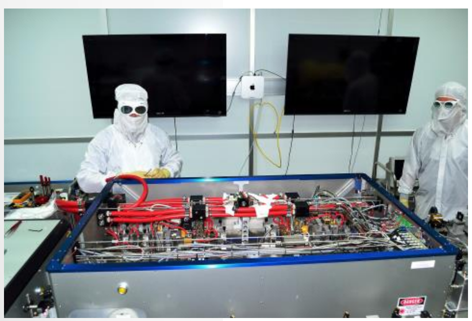
High quality optics – 40 kg
Surface RMS ~nm

Feedback loops from few Hz to few kHz

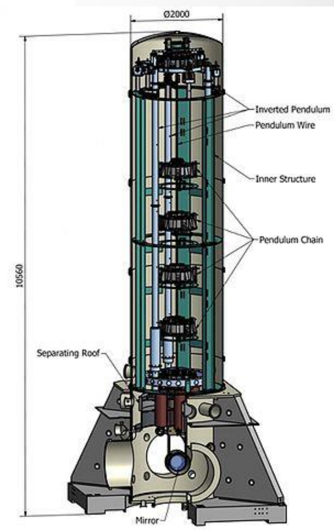


Fabry-Perot cavities

High power laser



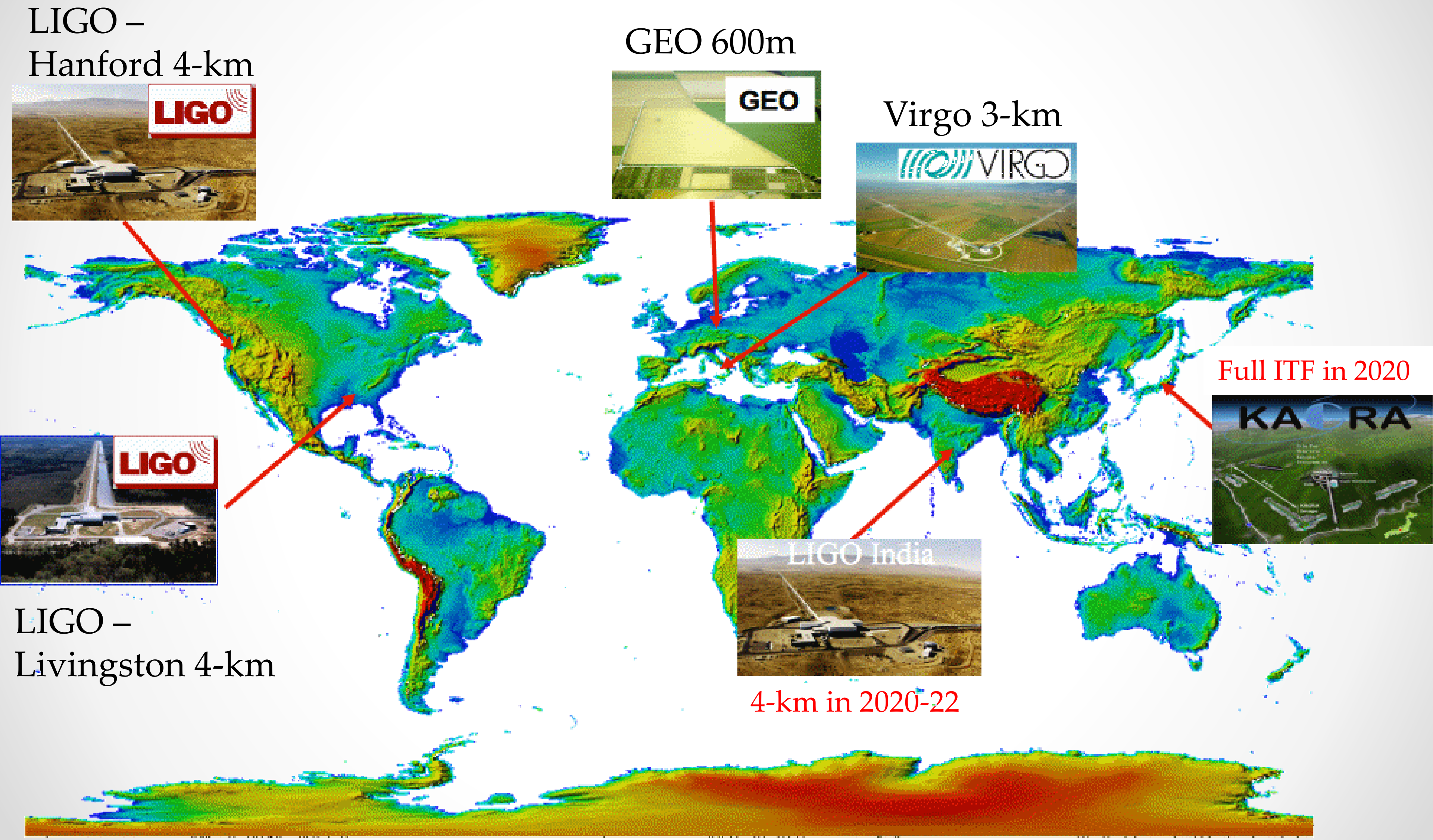
Full system under vacuum ~10^{-12} atm



Suspended Optics

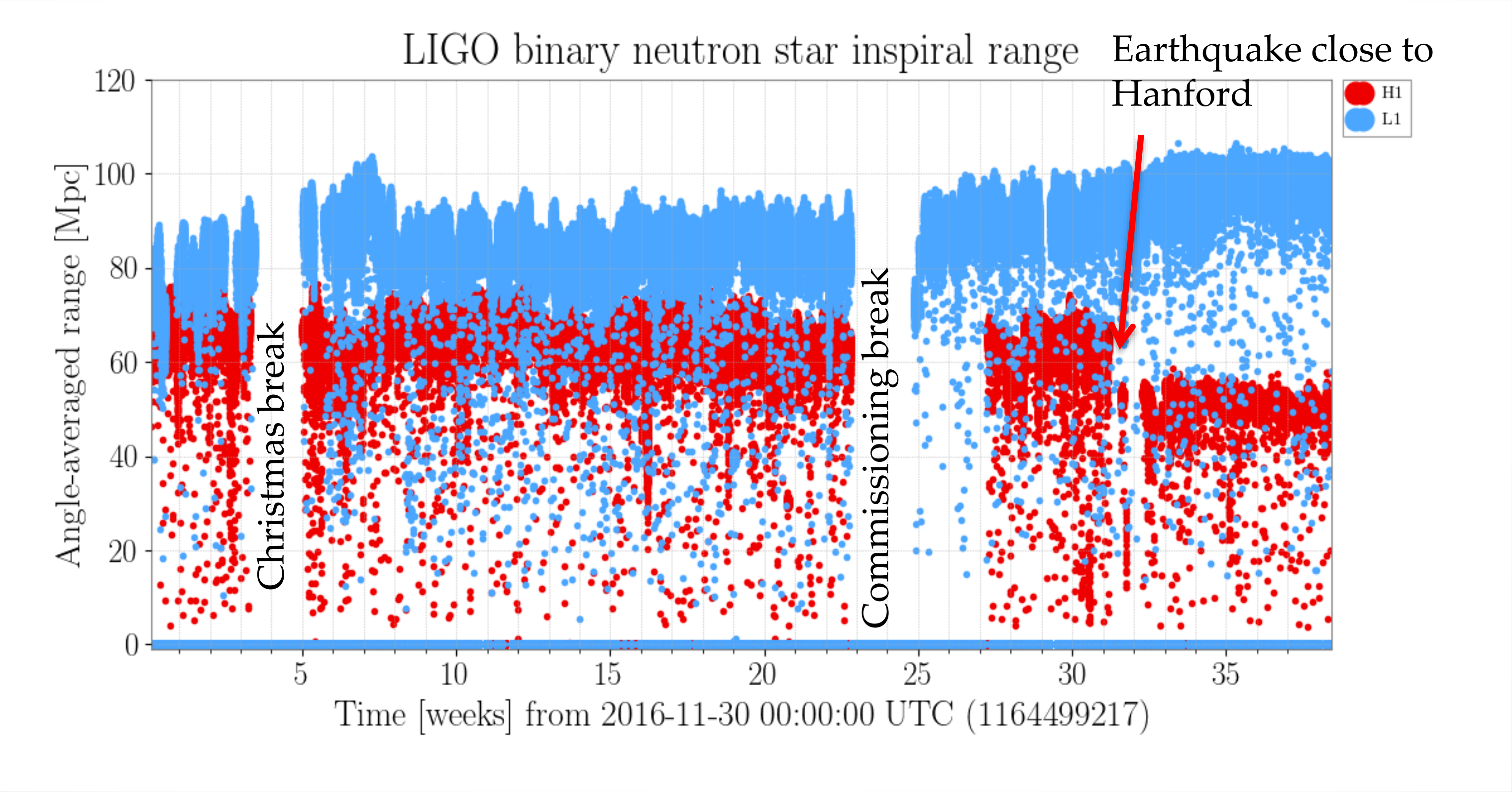
Attenuation 10^{14} @ 10 Hz

The GW detectors networks



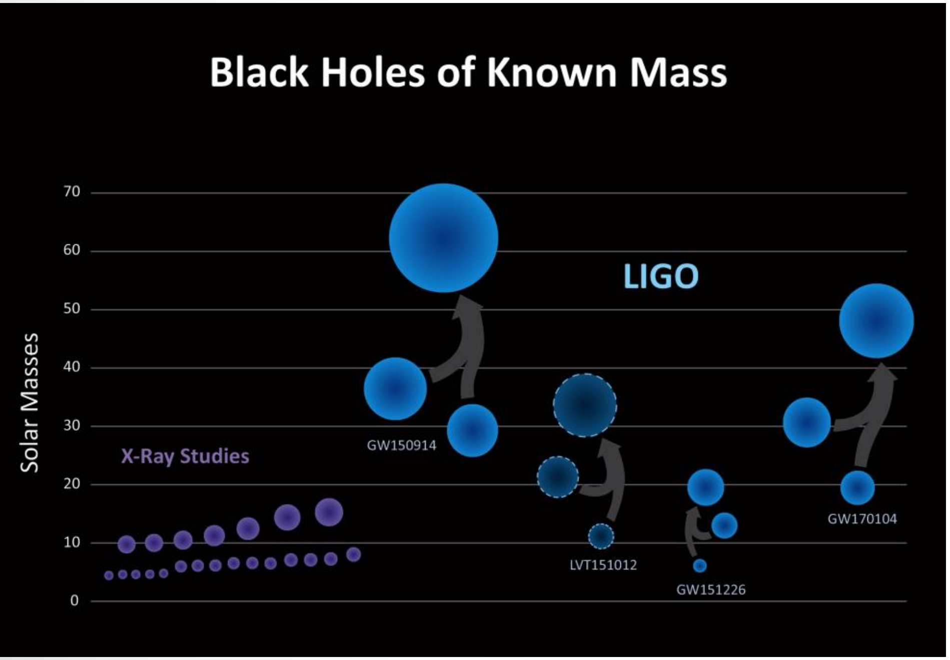
O2 run

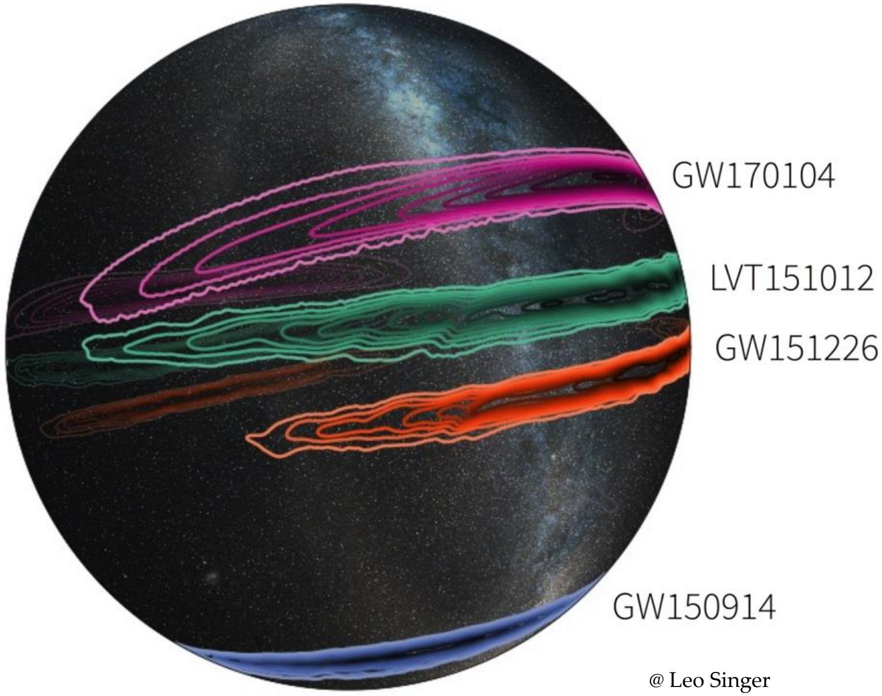
- From November 30th 2016 up to August 25th 2017, start with the two LIGO detectors only
- Duty cycle in coincidence for the two LIGO ~50 %
- Send possible candidate with FAR 1/2months



Detections after January 2017

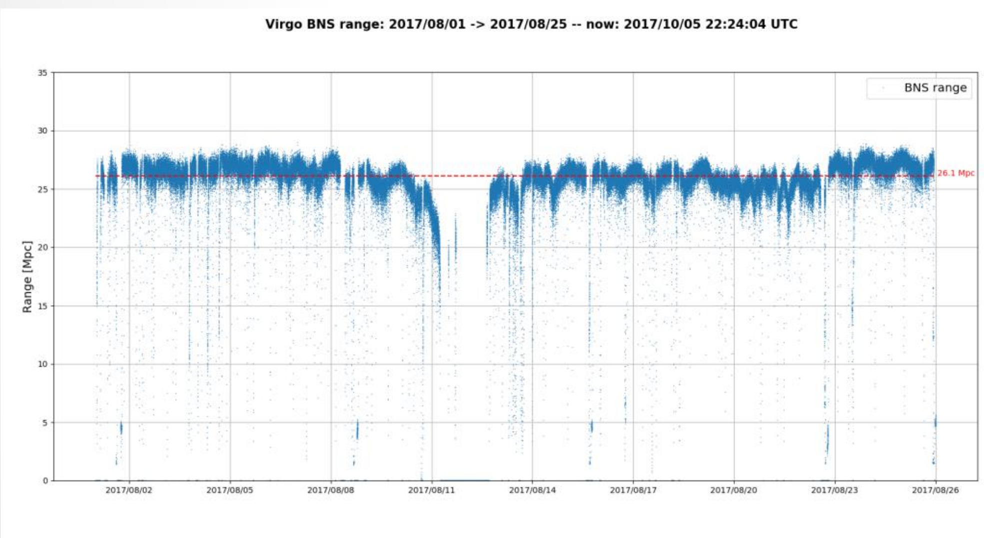
- Binary black hole with large sky localisation

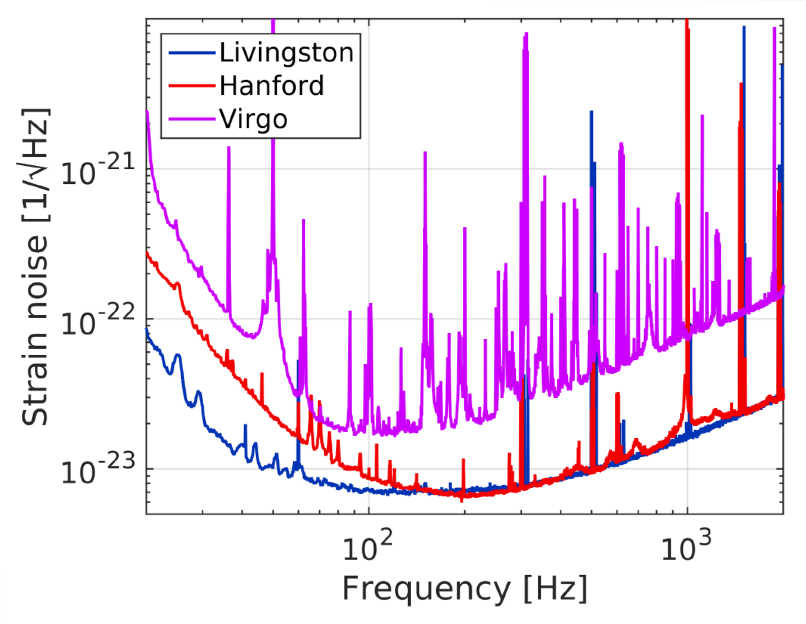




August 2017
an interesting summer

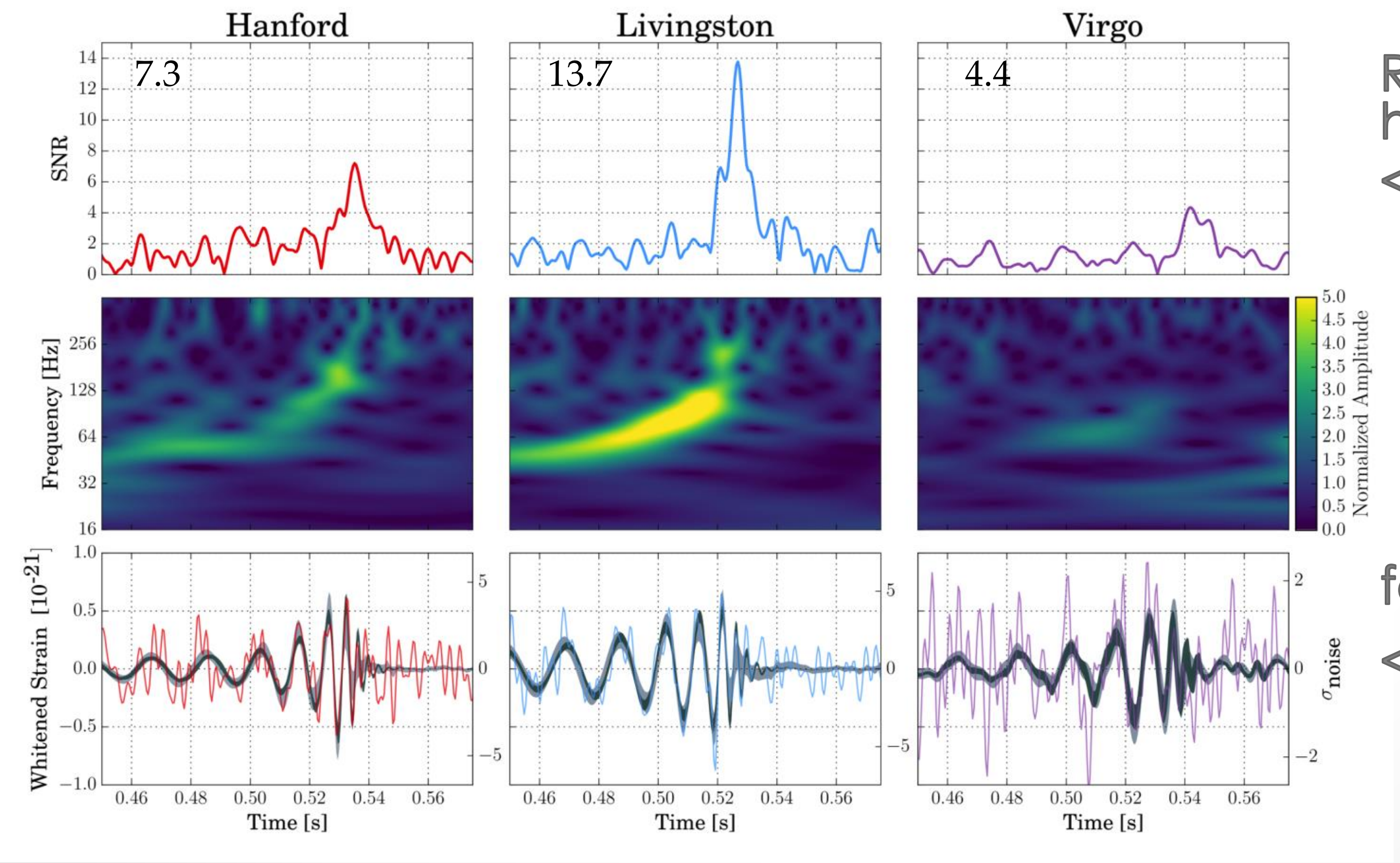
- Virgo joined August 1st 2017 for 25 days
- Duty cycle in triple coincidence ~60 %
  - Livingston : 77.6 %
  - Hanford : 75.8 %
  - Virgo : 82.4 %
- Several alerts sent during that month





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;



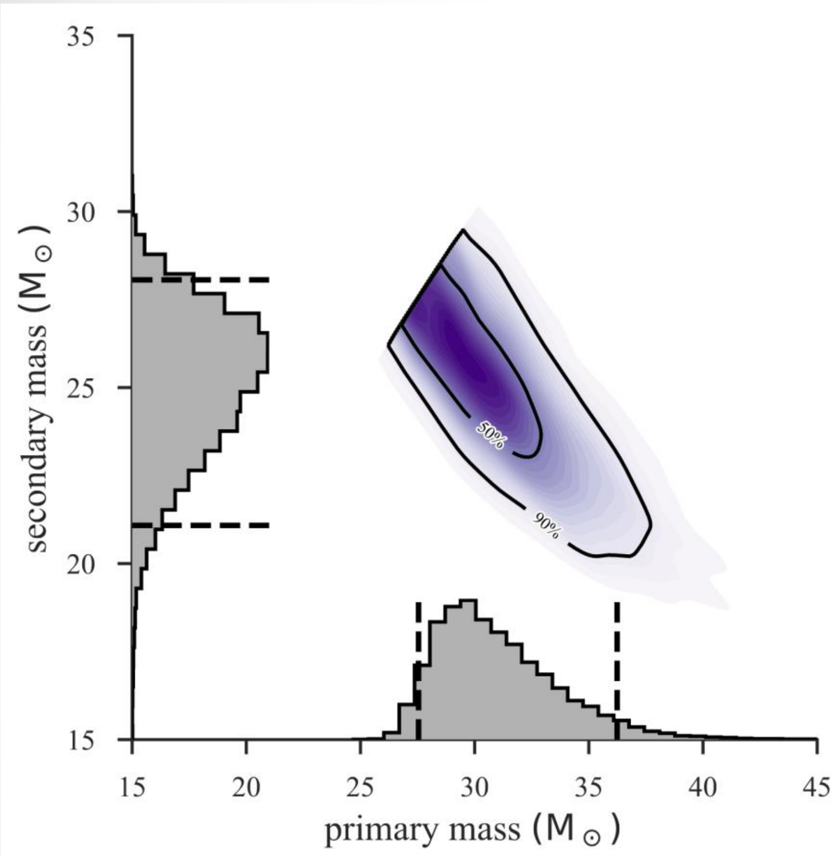
Random chance to have signal in Virgo < 0.3 %

false alarm rate

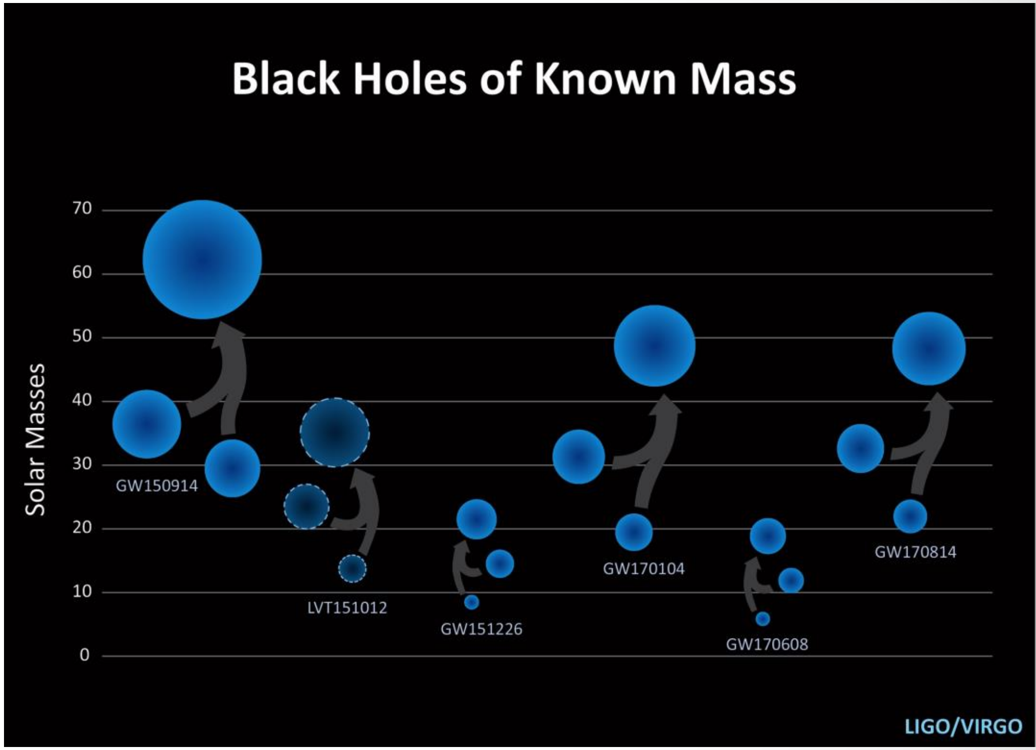
< 1 in140,000 years

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

A new binary black hole

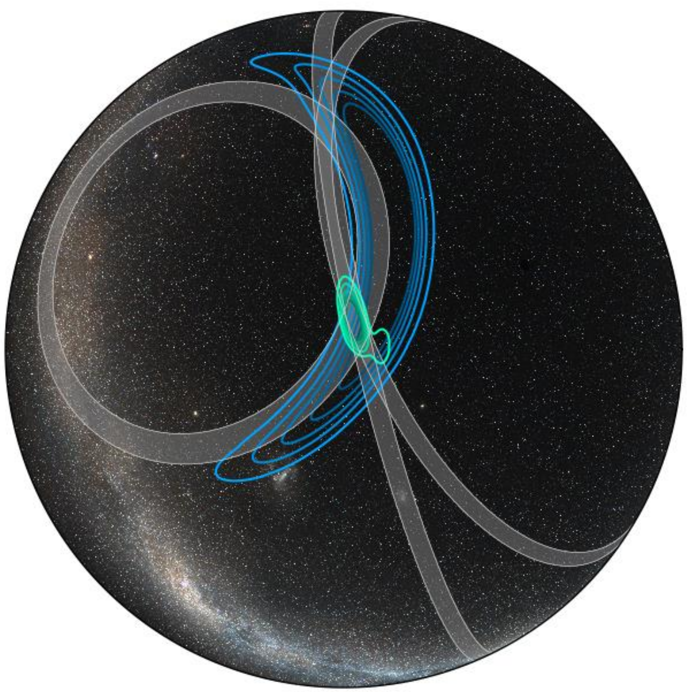


GW170814: A Three-Detector Observation of Gravitational Waves
from a Binary Black Hole Coalescence, Abbott *et al.* , PRL 119, 141101

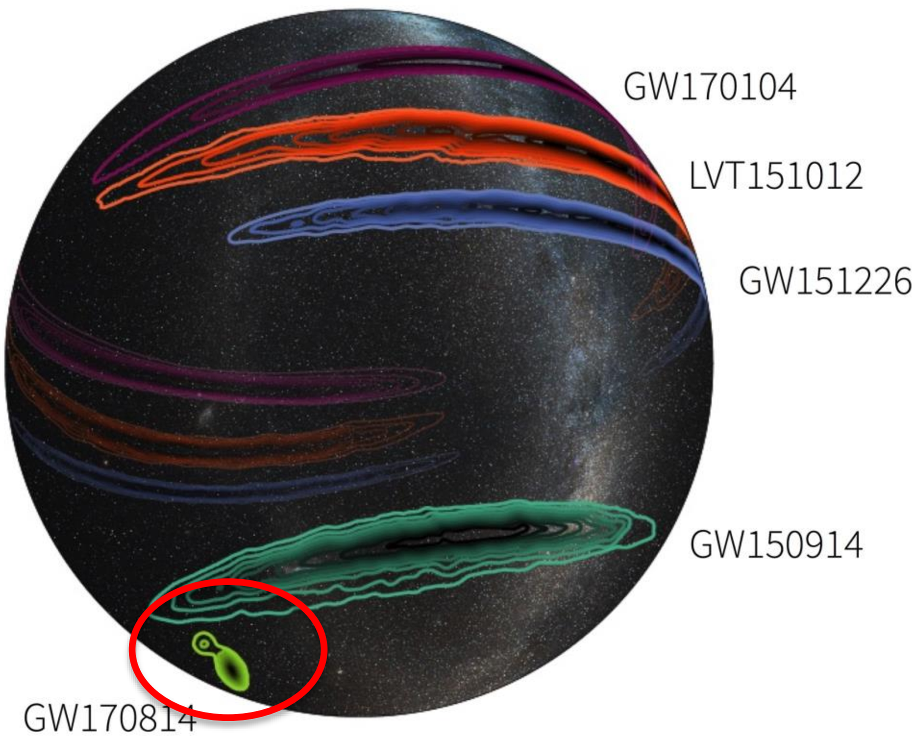


Better sky localisation

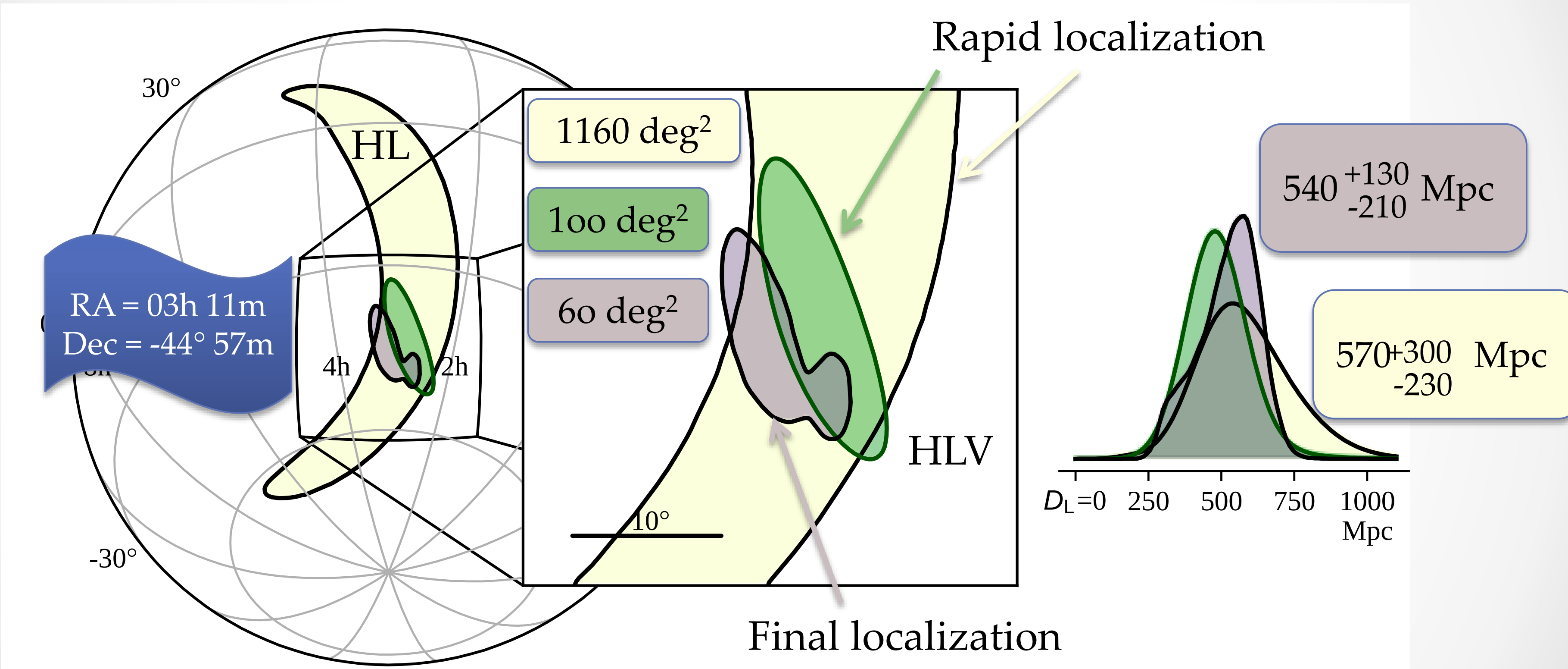
(compare to LIGO only)



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



Source parameters improvements



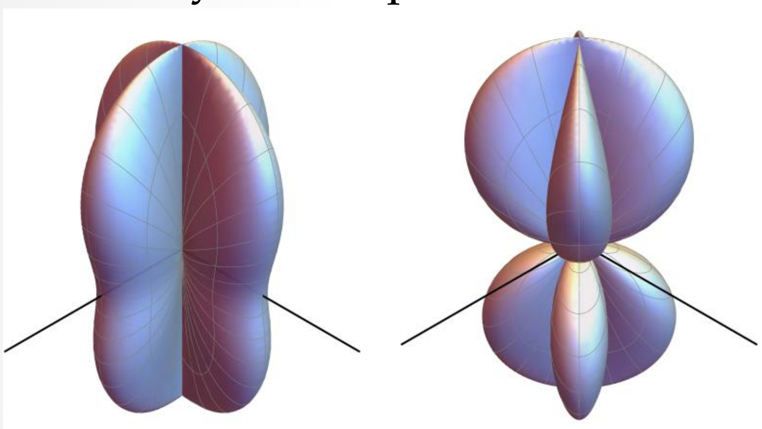
Error in sky area : factor 20 !
Reduced incertitude in distance by 1.5

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

Polarization in GR

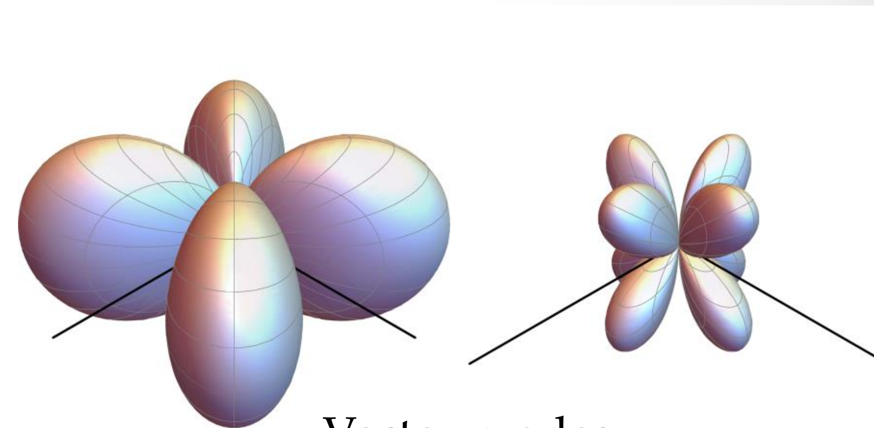
- With a third detector (non aligned) : test new types of polarization

Only ones expected with GR



Tensor modes

Allowed by other gravitation theories

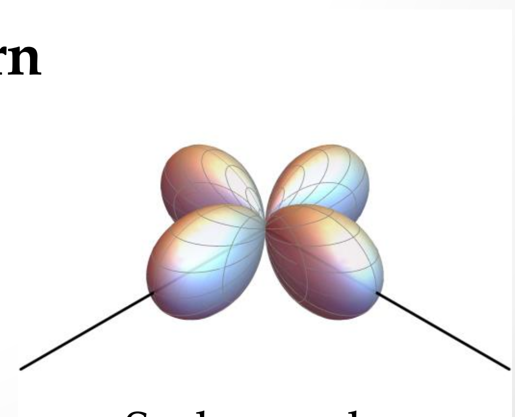


Vector modes

Antenna pattern

Favor pure tensor vs pure vector or scalar

Cannot conclude on mixed version

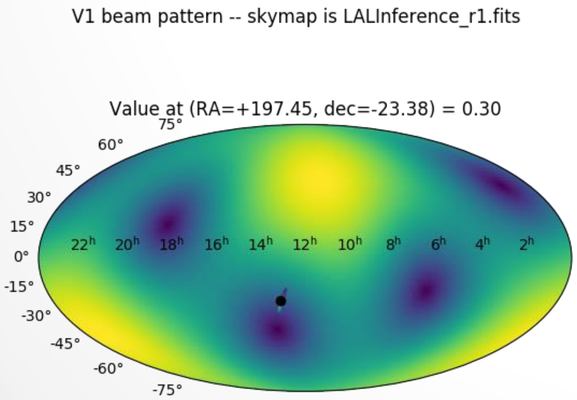


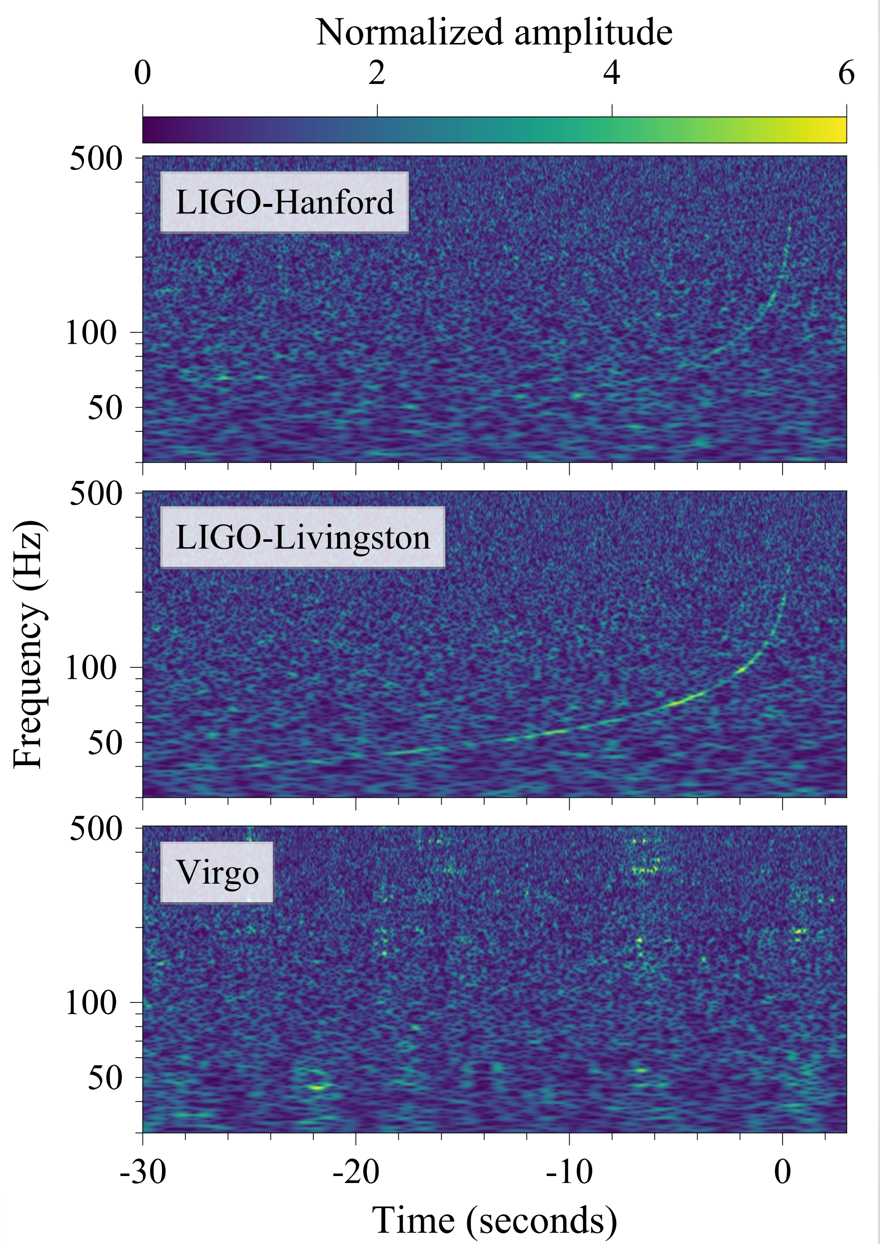
Scalar modes

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

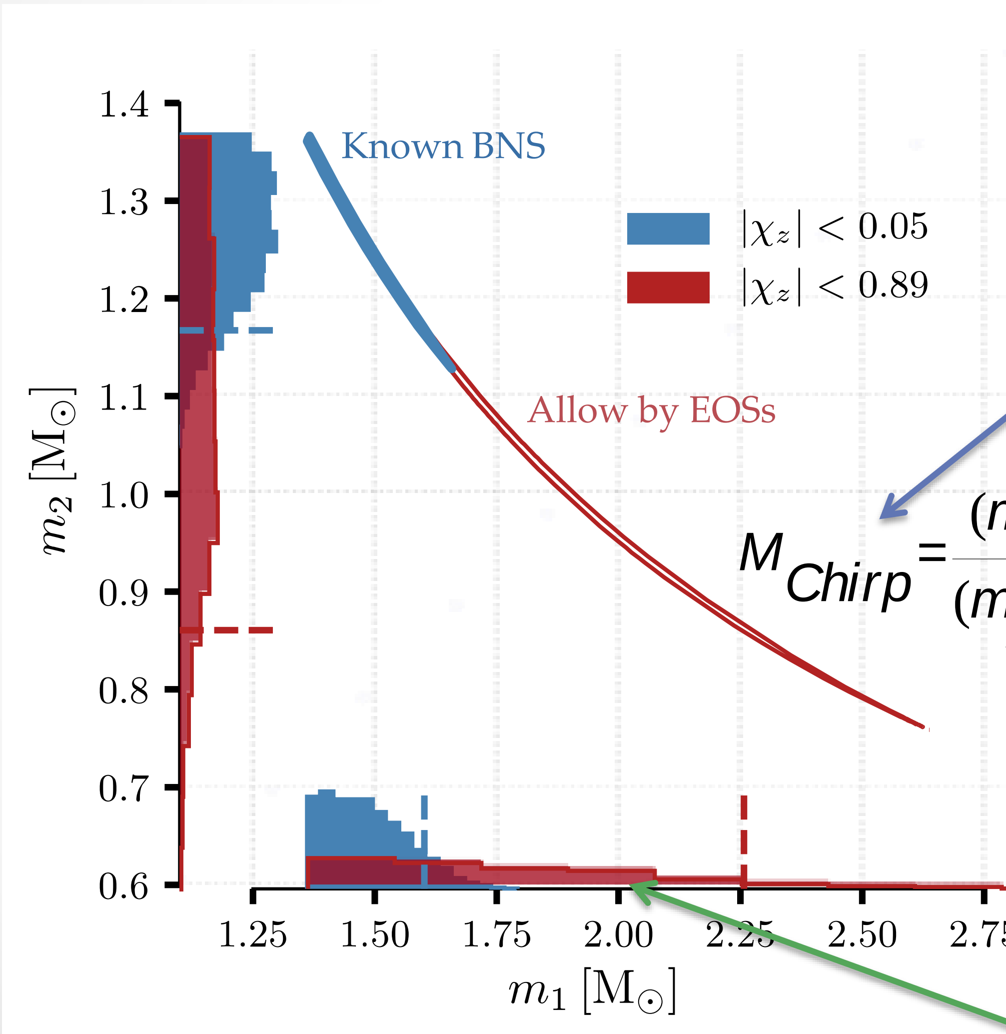
17^{th} of August

- 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





Masses



3000 cycles in the detector frequency band

$$M_{Chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = 1.188^{+0.004}_{-0.002} M_\odot$$

Largest known mass for NS

Source parameters

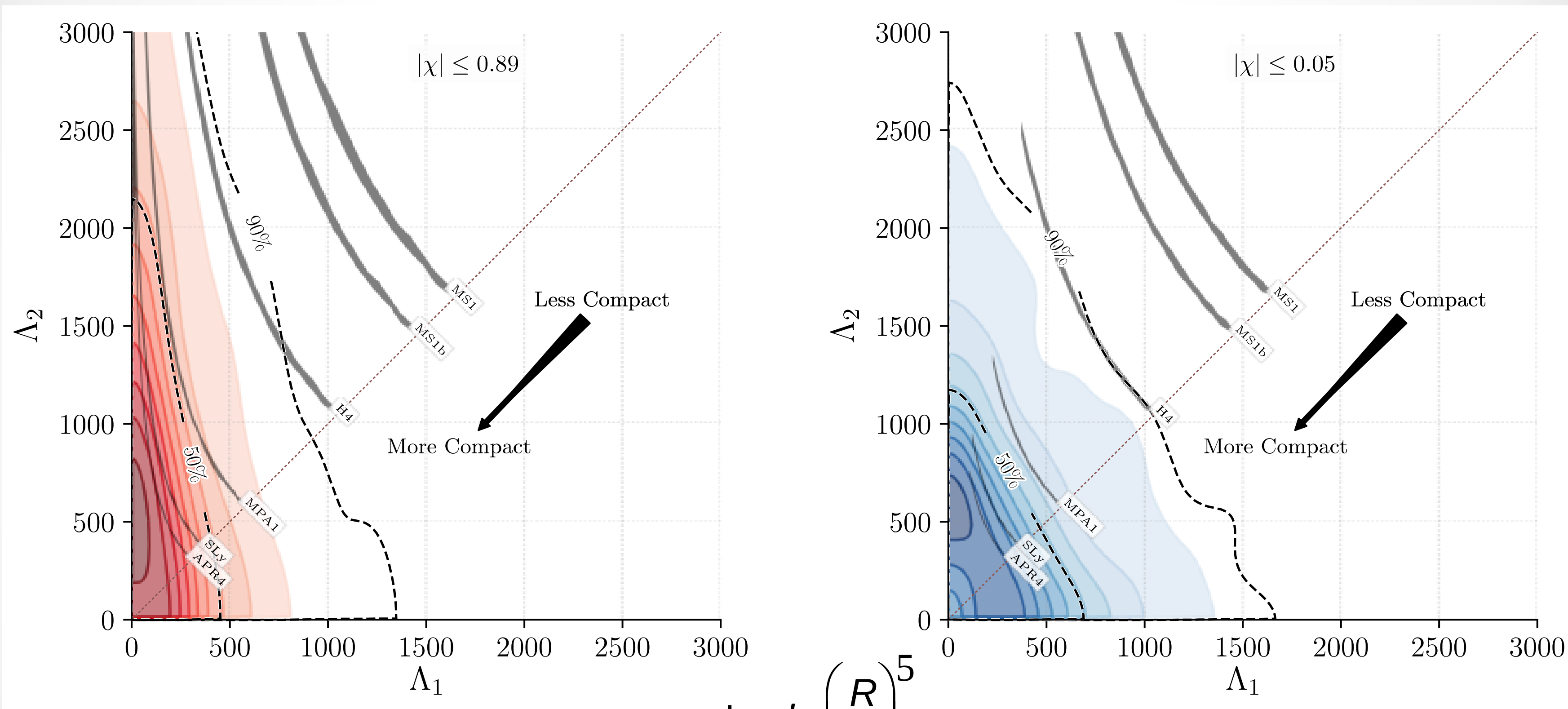
GW170817 : Observation of gravitational waves from a binary neutron star inspiral, PRL 2017

	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 $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}\ {\rm M}_\odot$	$2.82^{+0.47}_{-0.09}\ {\rm M}_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025\ {\rm M}_\odot\ {\rm c}^2$	$> 0.025\ {\rm M}_\odot\ {\rm c}^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Misalignment of total angular momentum and line of sight	$\lesssim 56°$	$\lesssim 55°$
using counterpart location	$\lesssim 30°$	$\lesssim 30°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\lesssim 800$	$\lesssim 700$
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	$\lesssim 800$	$\lesssim 1400$

	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination $\theta_{\rm JN}$	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination $\theta_{\rm JN}$ using EM distance constraint [104]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001}{\rm M}_\odot$	$1.1976^{+0.0004}_{-0.0002}{\rm M}_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}{\rm M}_\odot$	$1.186^{+0.001}_{-0.001}{\rm M}_\odot$
Primary mass m_1	(1.36, 1.60) ${\rm M}_\odot$	(1.36, 1.89) ${\rm M}_\odot$
Secondary mass m_2	(1.16, 1.36) ${\rm M}_\odot$	(1.00, 1.36) ${\rm M}_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}{\rm M}_\odot$	$2.77^{+0.22}_{-0.05}{\rm M}_\odot$
Mass ratio q	(0.73, 1.00)	(0.53, 1.00)
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin χ_1	(0.00, 0.04)	(0.00, 0.50)
Secondary dimensionless spin χ_2	(0.00, 0.04)	(0.00, 0.61)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190}(symmetric)/ 300^{+420}_{-230}(HPD)	(0, 630)

Properties of the binary neutron star merger GW170817, Abbott et al, submitted to PRX, 2018

Equation of state (EOS)



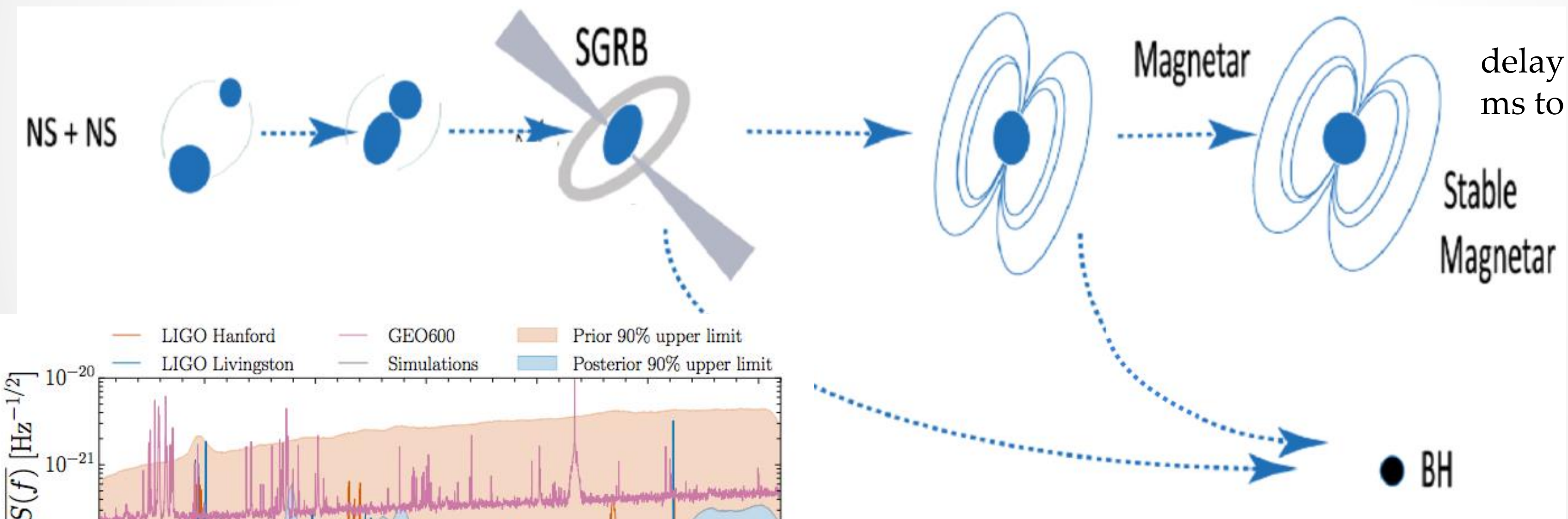
$$L \propto k_2 \left(\frac{R}{m}\right)^5$$

- Signal observed favour EOS for compact NS

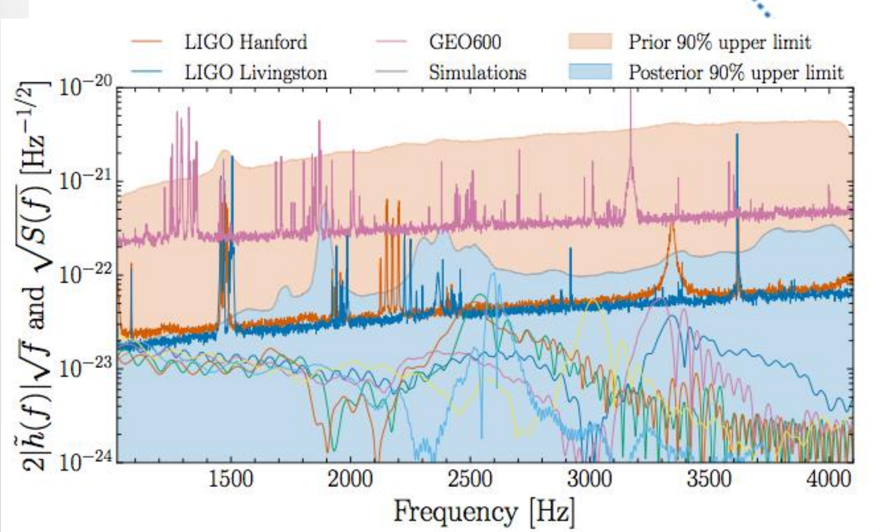
Remanent object

- Different scenarios are possible
- Not yet possible to conclude with GW signal only

Signal from ms to 10s ks



delay between ms to 10s of ks



QNM ≥ 6kHz

Signal ~ ms

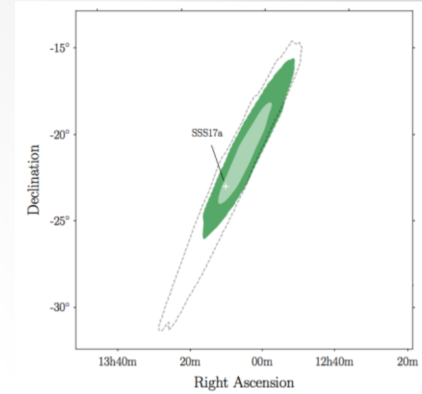
Properties of the binary neutron star merger GW170817, Abbott et al, submitted to PRX, 2018

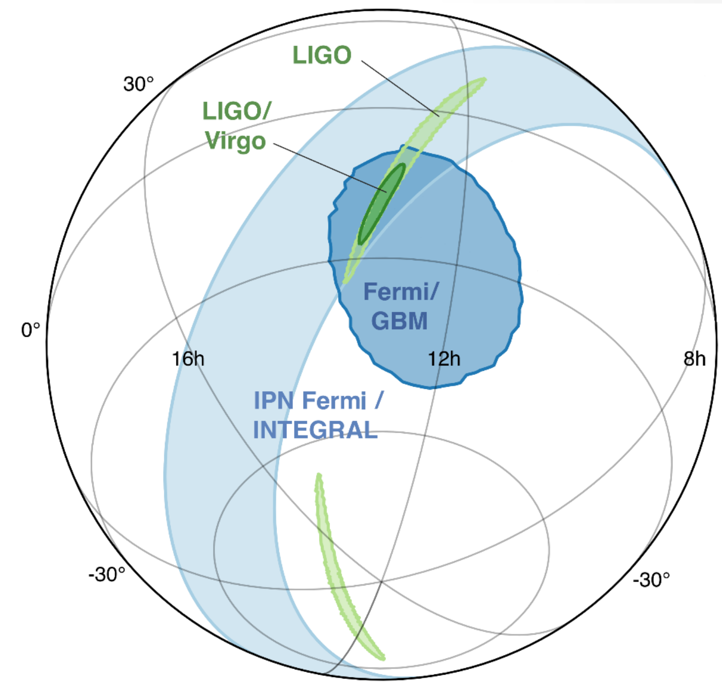
Key role from Virgo in the localisation

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 !!

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)

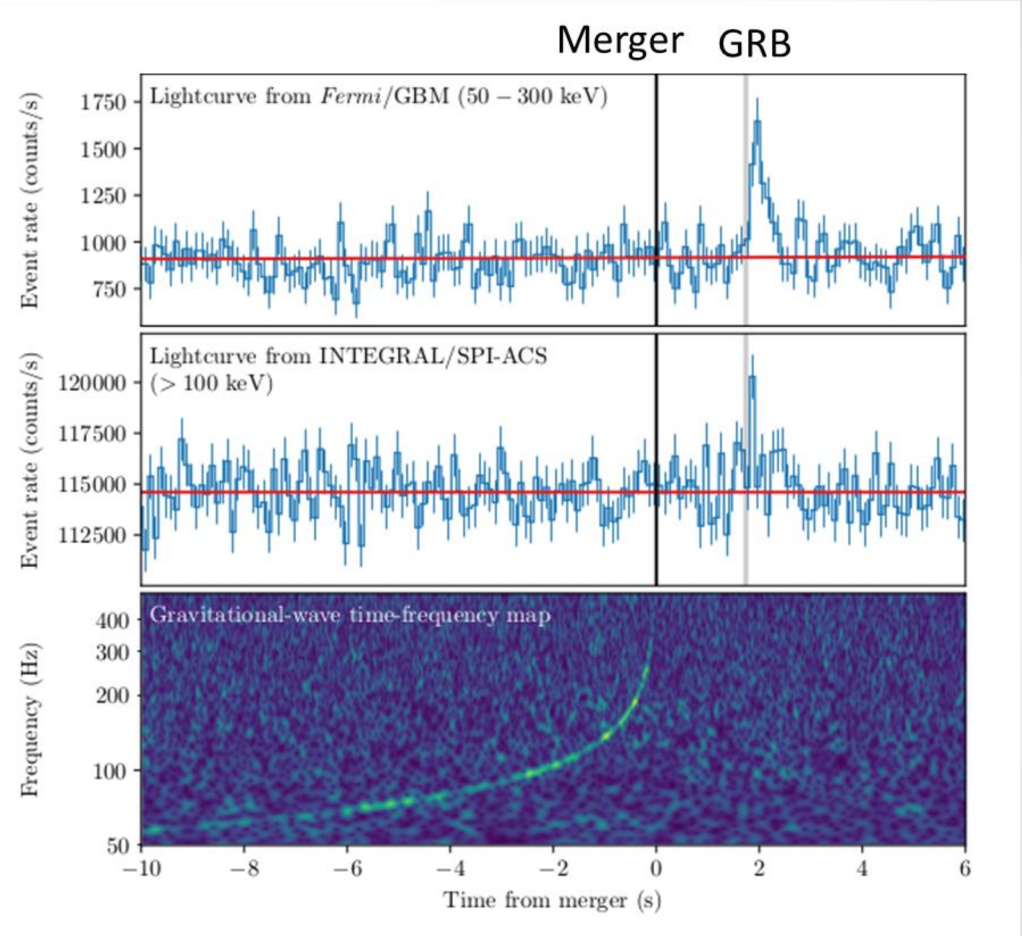
+16 s — GRB alert sent

+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) $< 5\ 10^{-8}$

17/08/2017 12:41:04 — GW170817

+2 s — GRB170817A

+5h — Localisation with GW
Distance 40 Mpc

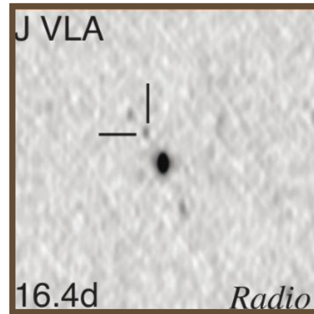
+11h — Discovery of kilonova AT2017gfo by Swope
Find host galaxy : NGC4993
START CAMPAIGN ON AT2017GFO

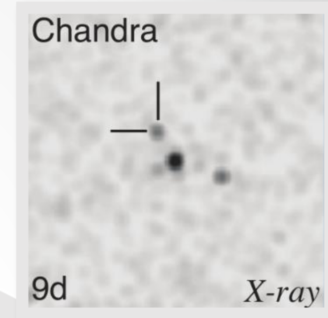
+1.2j — First spectra of the kilonova

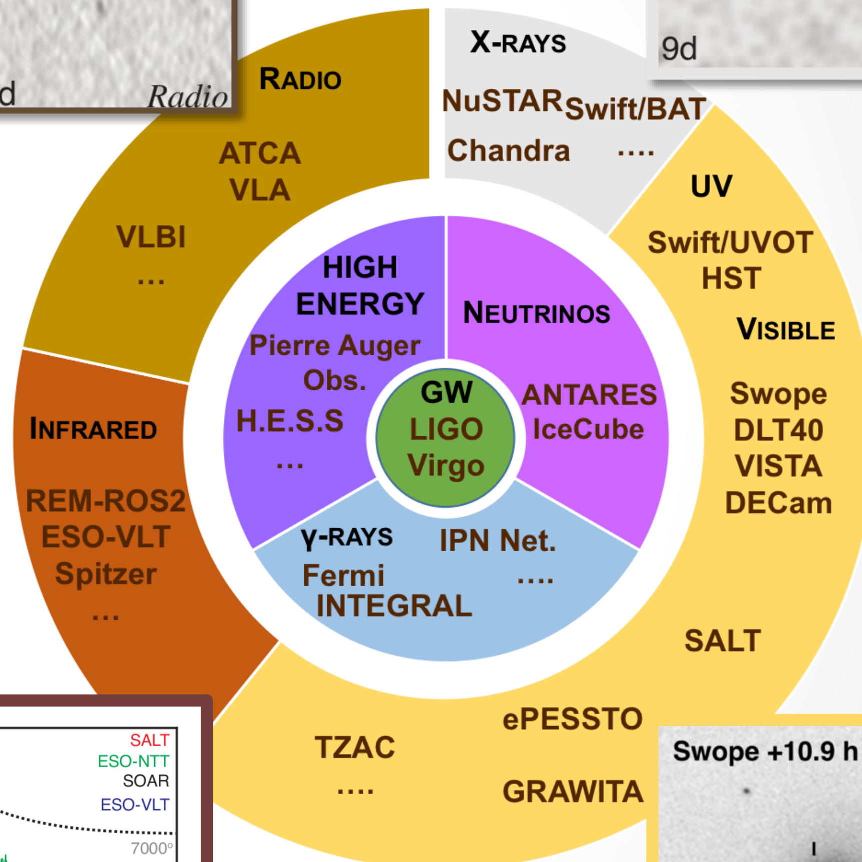
+9j — Discovery of an X-ray counterpart

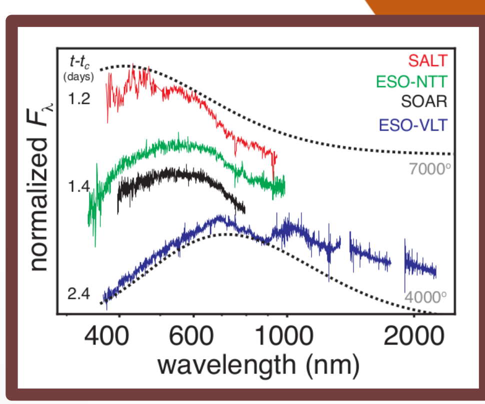
+16j — First radio signal found with VLA

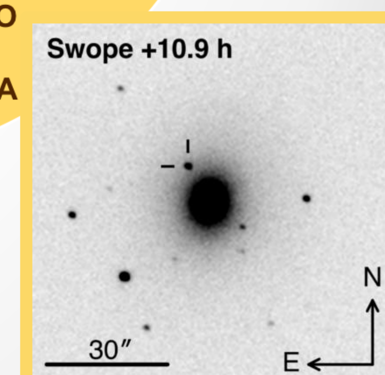
+150j — Observation in X increasing





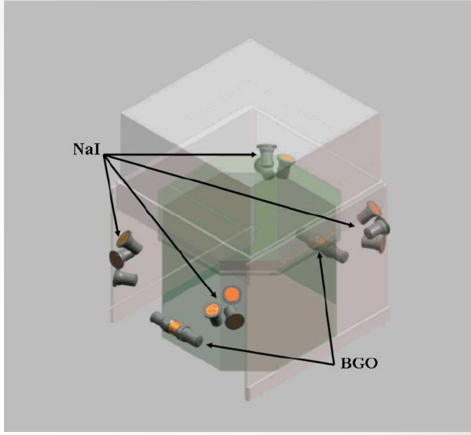




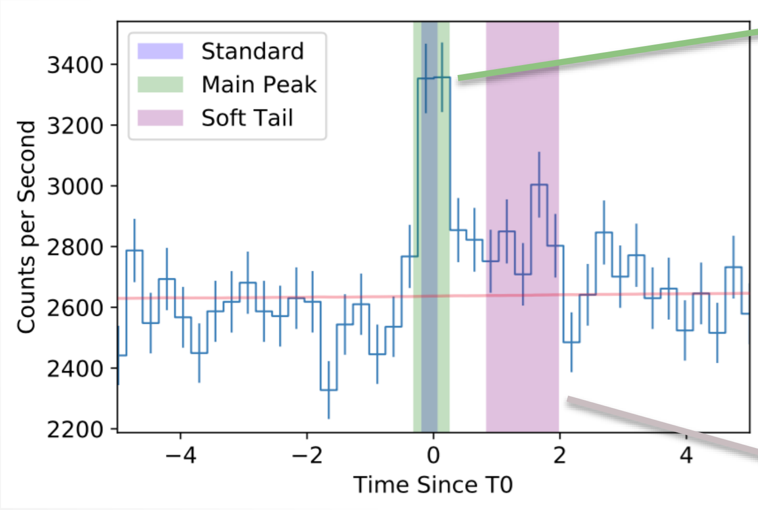


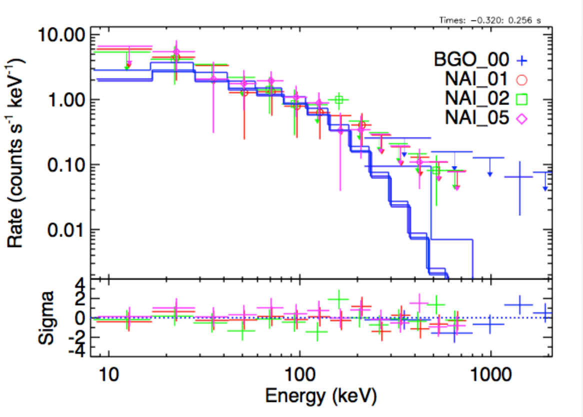
« Multi-messenger observations of a binary neutron star merger », Abbott et al., ApJ, 2017

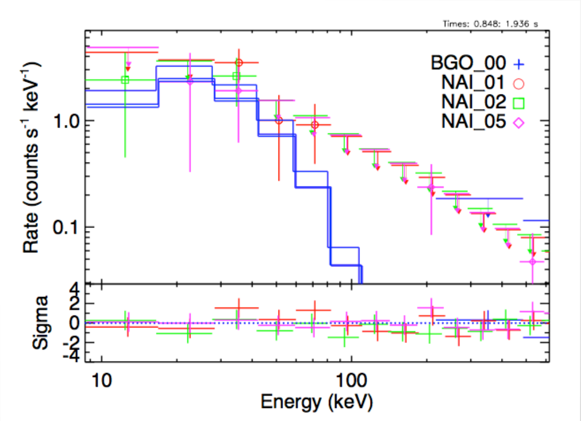
GRB detection



- Burst detected on board by in 3/12 GBM detectors
- Weak event $E_{iso} = 3.1 \pm 0.7\ 10^{46}$ erg
- Duration : 2 ± 0.5 s – shift with GW 1.74 ± 0.05 s
- Confirmed by offline analysis using Integral/SPI-ACS

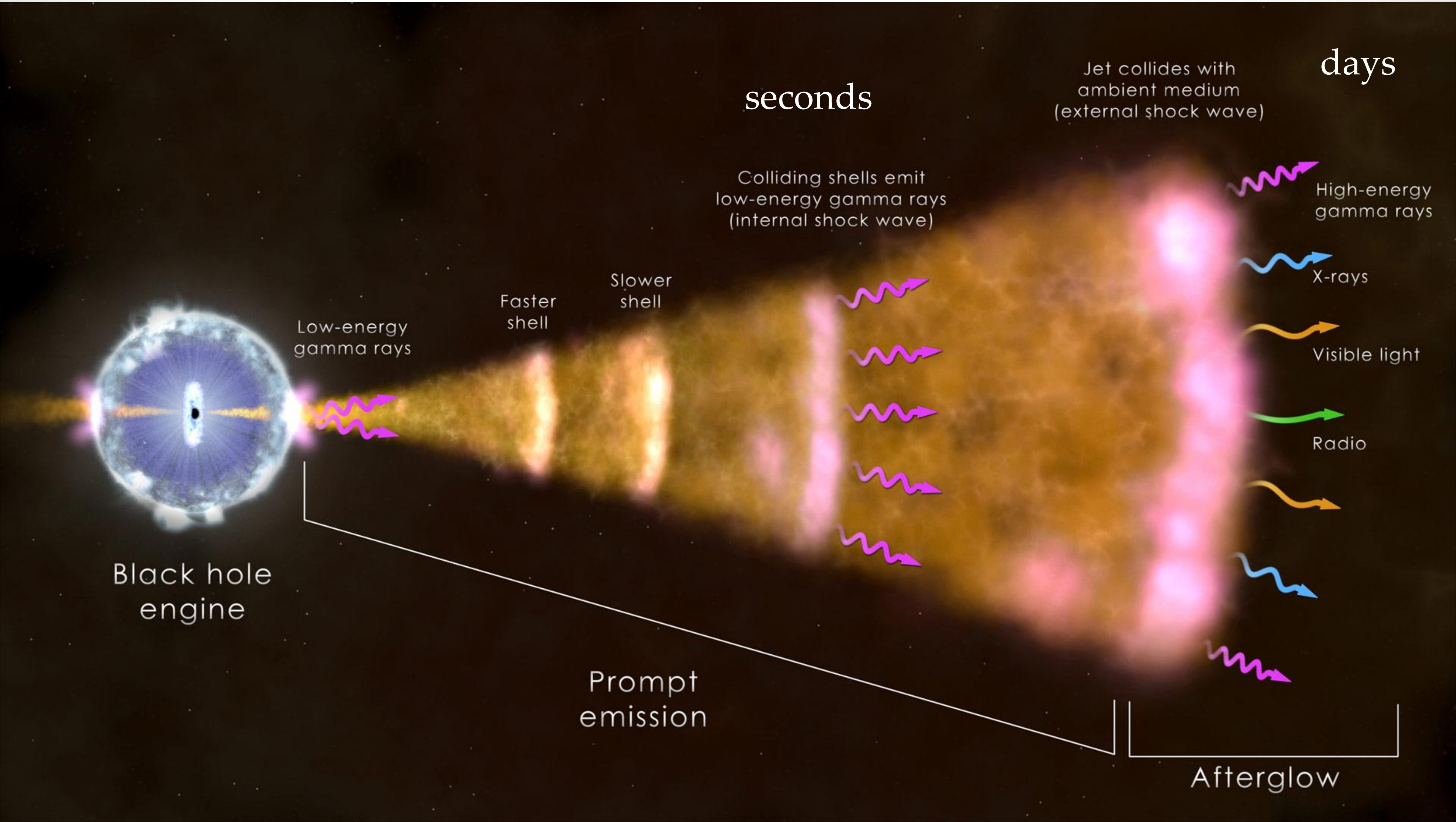






Goldstein, A., et al., "An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi-GBM Detection of GRB 170817A." 2017, ApJL, Vol. 848, issue 2,

Model for short gamma-ray bursts



Common GW-GRB analysis

Test for fundamental physics using time delay and source distance

- Speed of gravity : $-3\times10^{-15} \le \frac{v_{GW} - v_{EM}}{v_{EM}} \le +7\times10^{-16}$

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

gravitational potential

$$-2.6\times10^{-7} \le \gamma_{GW} - \gamma_{EM} \le 1.2\times10^{-6}$$

Deviation to Einsten-Maxwell

- Lorentz Invariance violation :

Improve between a factor 2 and 10^{10} previous constraints

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

Common GW-GRB analysis

Astrophysical impact

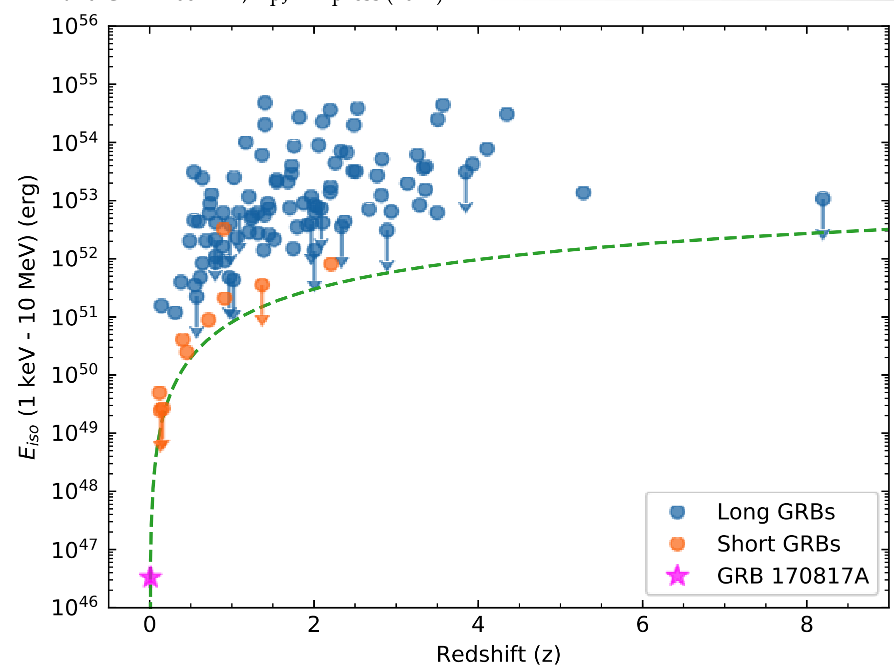
- Short timescale : fireball model with internal shock
- Softer component could come from photosphere of the fireball
- Time delay could then be due to :
  - Propagation of the shells in the jets
  - Time needed for the fireball to become optically thin to gamma-rays
- Constraints to EOS – we need to create a jet to produce the GRB

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

Is this a standard short GRB ?

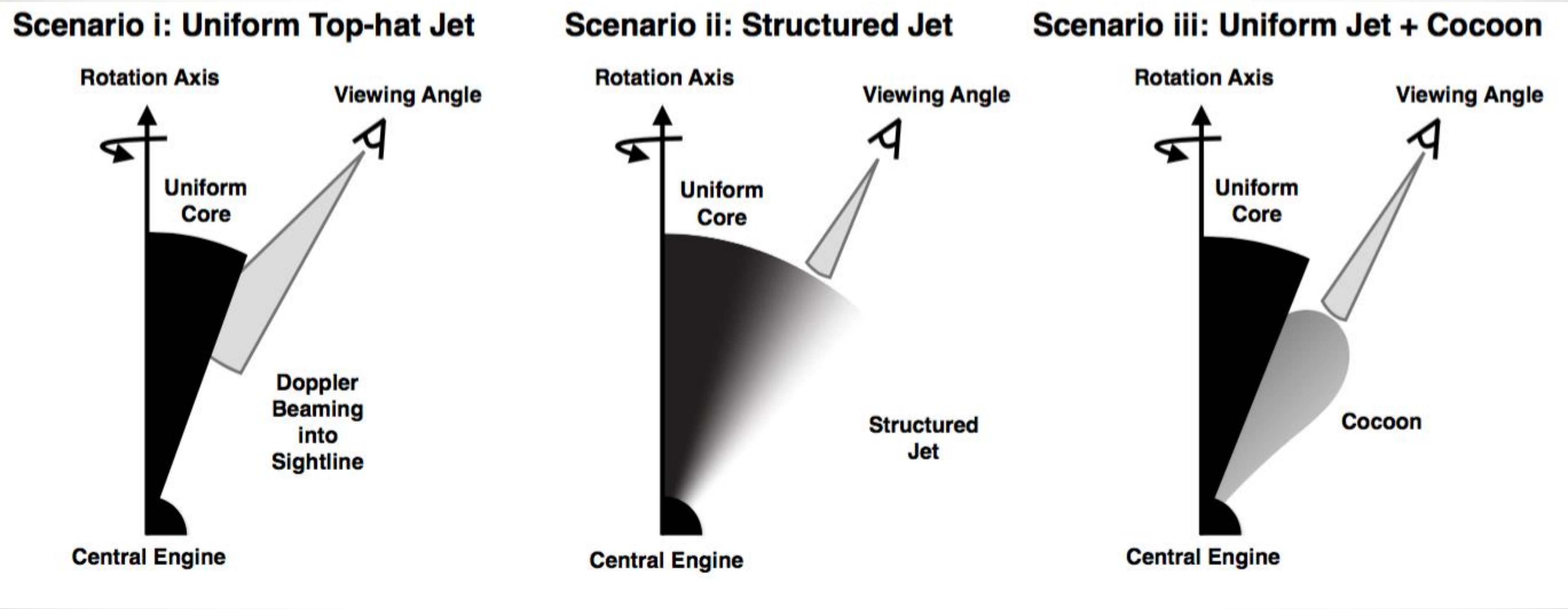
- Light curve and spectra shape : usual short GRB
- 2 to 6 order of magnitude less energetic than previously detected
- 100 times closer to previous short GRB with a measured distance
- A similar GRB could have been detected by GBM on board up to 80 Mpc

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



Possible scenarios

- Is dimness intrinsic to the GRB, could it be a perspective effect or a structure ?

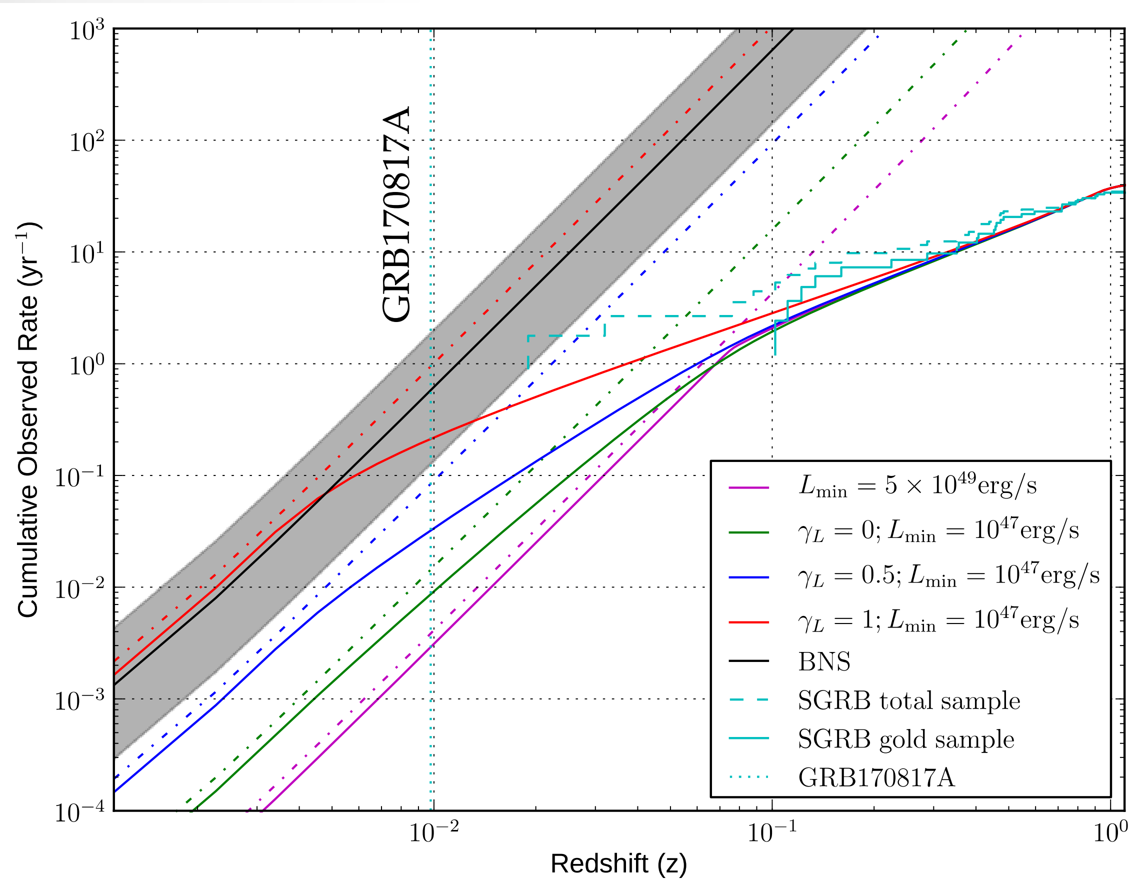


- Could it be a sub luminous class of short GRB ?
- Chandra observation later may favor off-axis or cocoon

"Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A", ApJL in press (2017)
Swift and *NuSTAR* observations of GW170817: detection of a blue kilonova, Evans et al, Science

Could we detect similar events ?

$$GW\ rate = 1540^{+3200}_{-1220}\ Gpc^{-3} y^{-1}$$



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

Known sGRB population 40/year

BNS detections (/year):

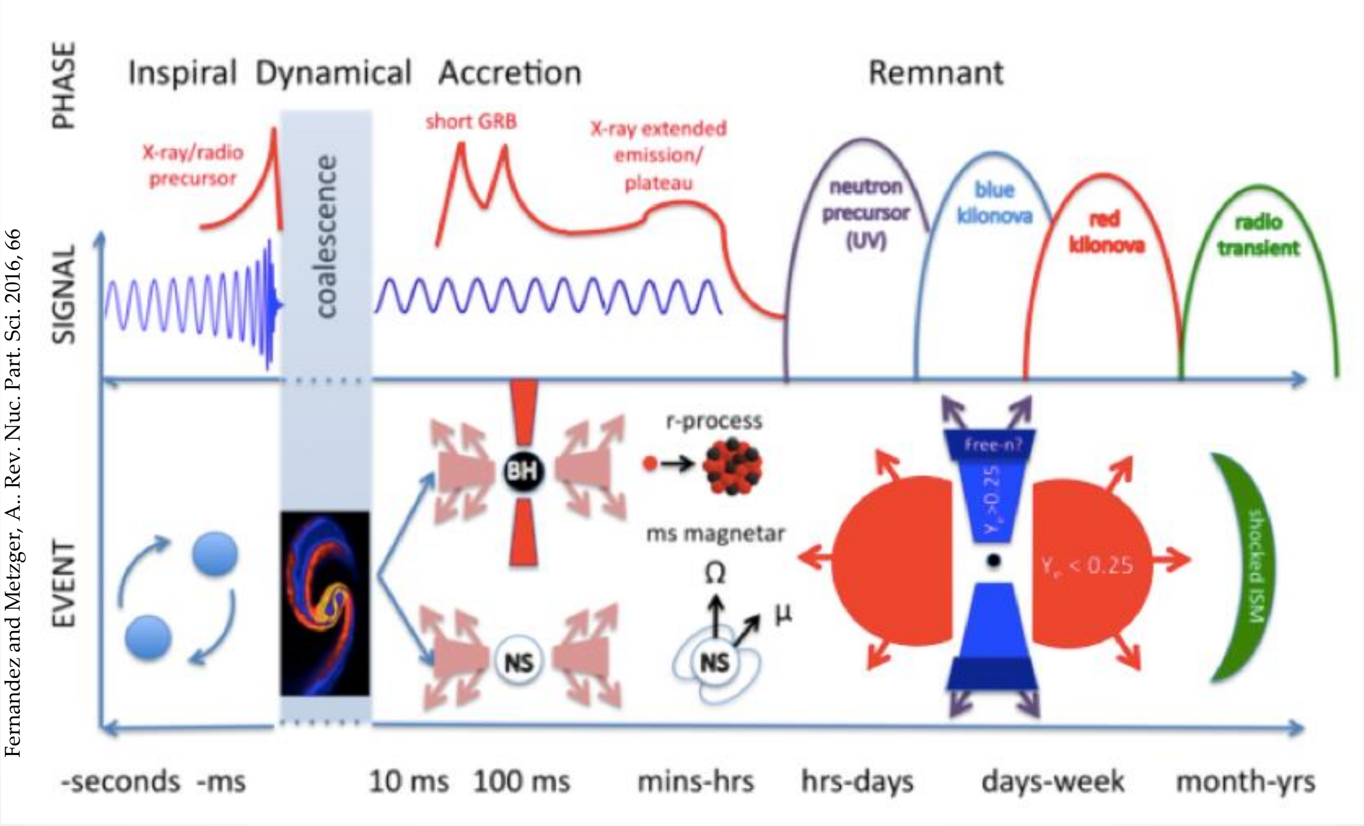
- O3 : 1-50
- Design : 6-120

GRB detections (/year):

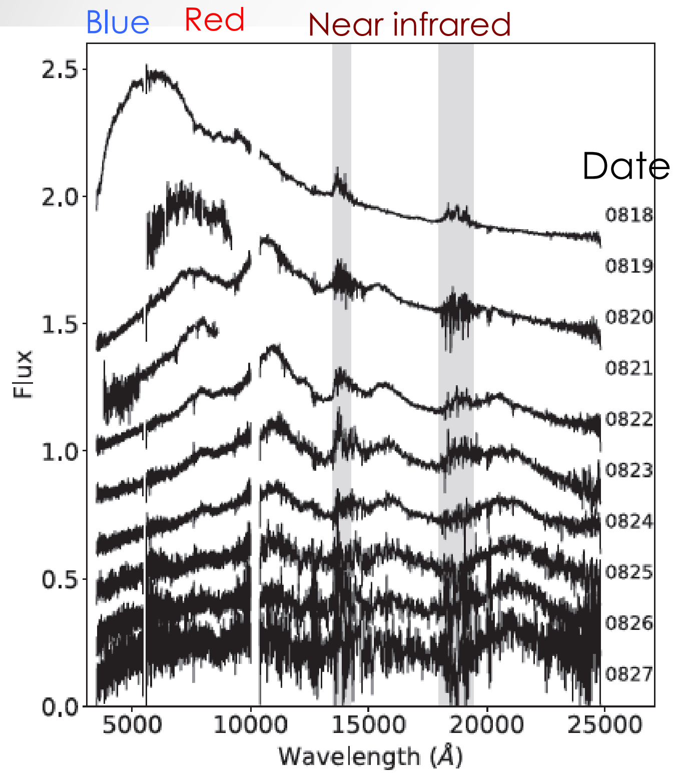
- O3 : 0.1-1.4
- Design : 0.3 – 1.7

Kilonova

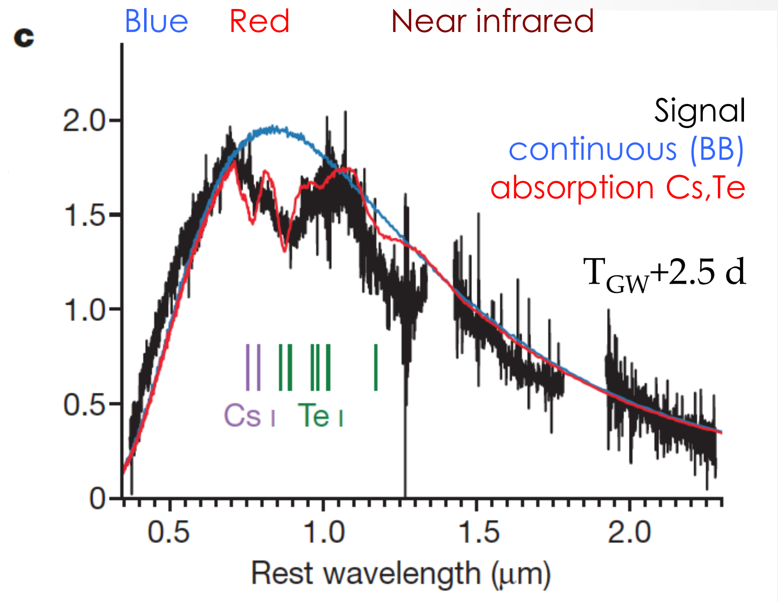
- During merger phase rich neutrons matter could produce heavy elements by neutron capture (r-process)
- Quasi isotrope emission, heated by radioactivity, emission expected to shift from blue to red during cooling



Kilonova – spectral observations



Grawita Spectrum ESO/VLT & Gemini



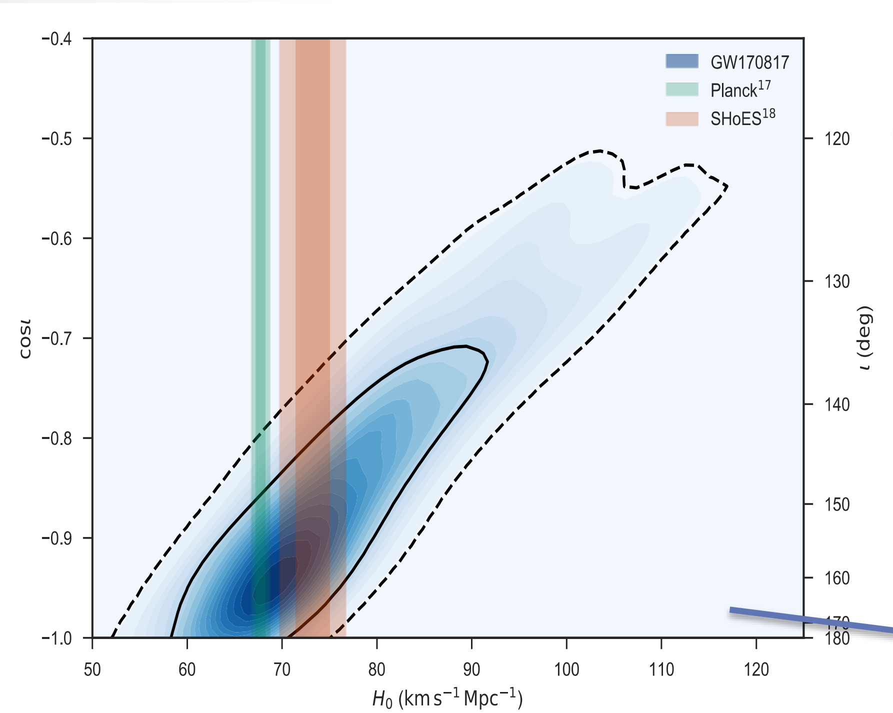
ePESSTO - Spectrum ESO/VLT & Gemini

- Spectrum favor a relativistic ejecta
- Rule out supernova hypothesis
- 11000 K at day 1, 5000 K a day later, 1400 K 10 days later
- Spectrum show contributions from heavy elements

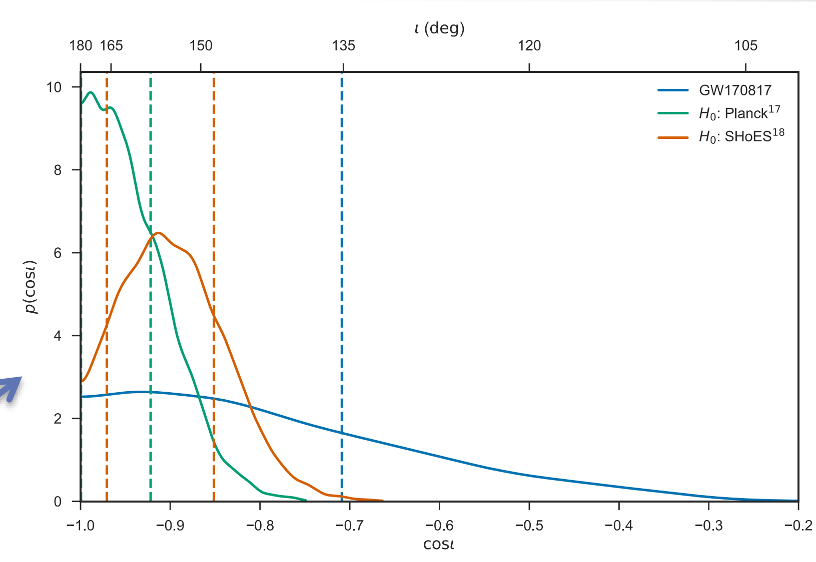
Hubble constant measurement

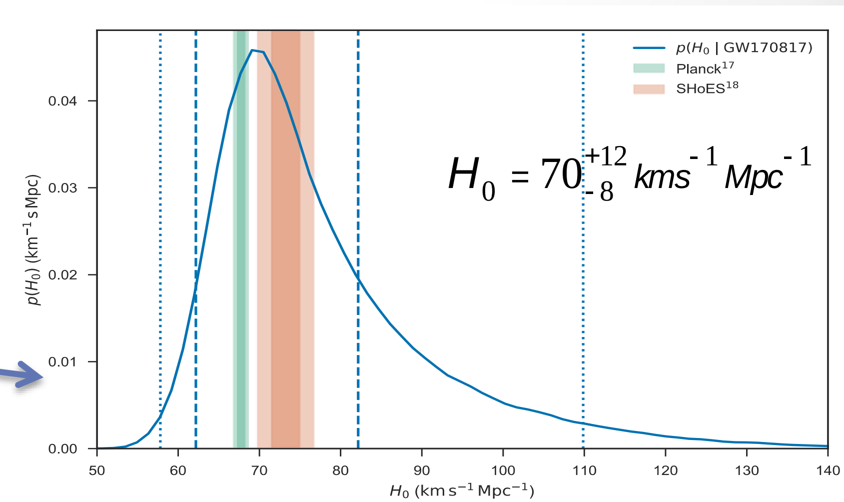
- For closed-by source : $v=H_0D$
- Distance (GW) and orientation are correlated

$$h(t) \propto \frac{M_{chirp}^{5/6}}{D} f(\cos i)$$



"A standard siren measurement of the Hubble constant with GW170817", Nature in press (2017)



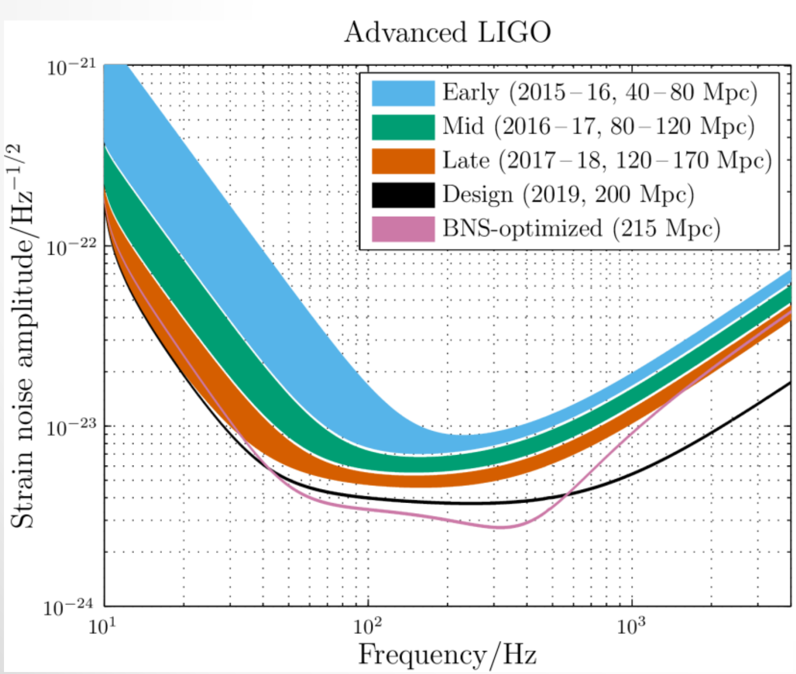


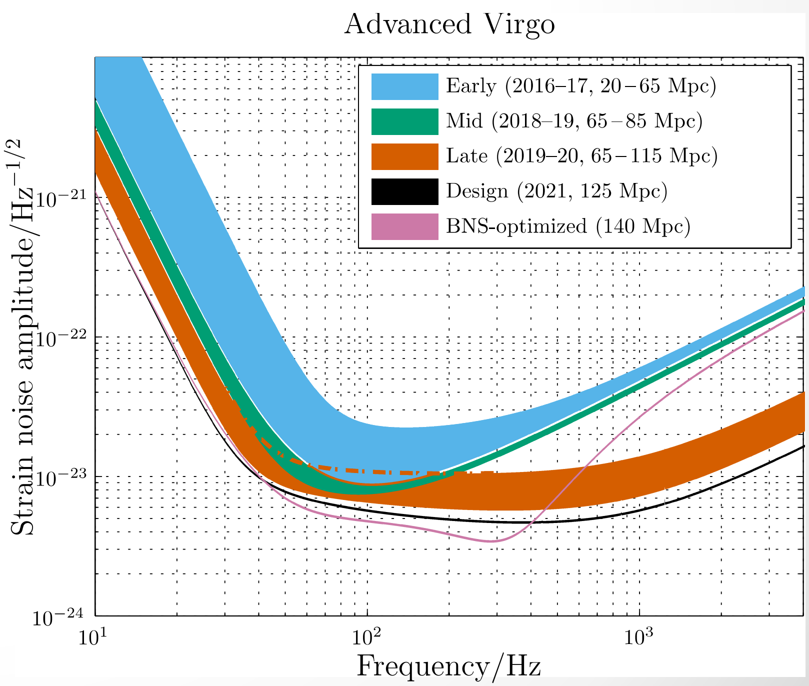
Main results with GW170817

- 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

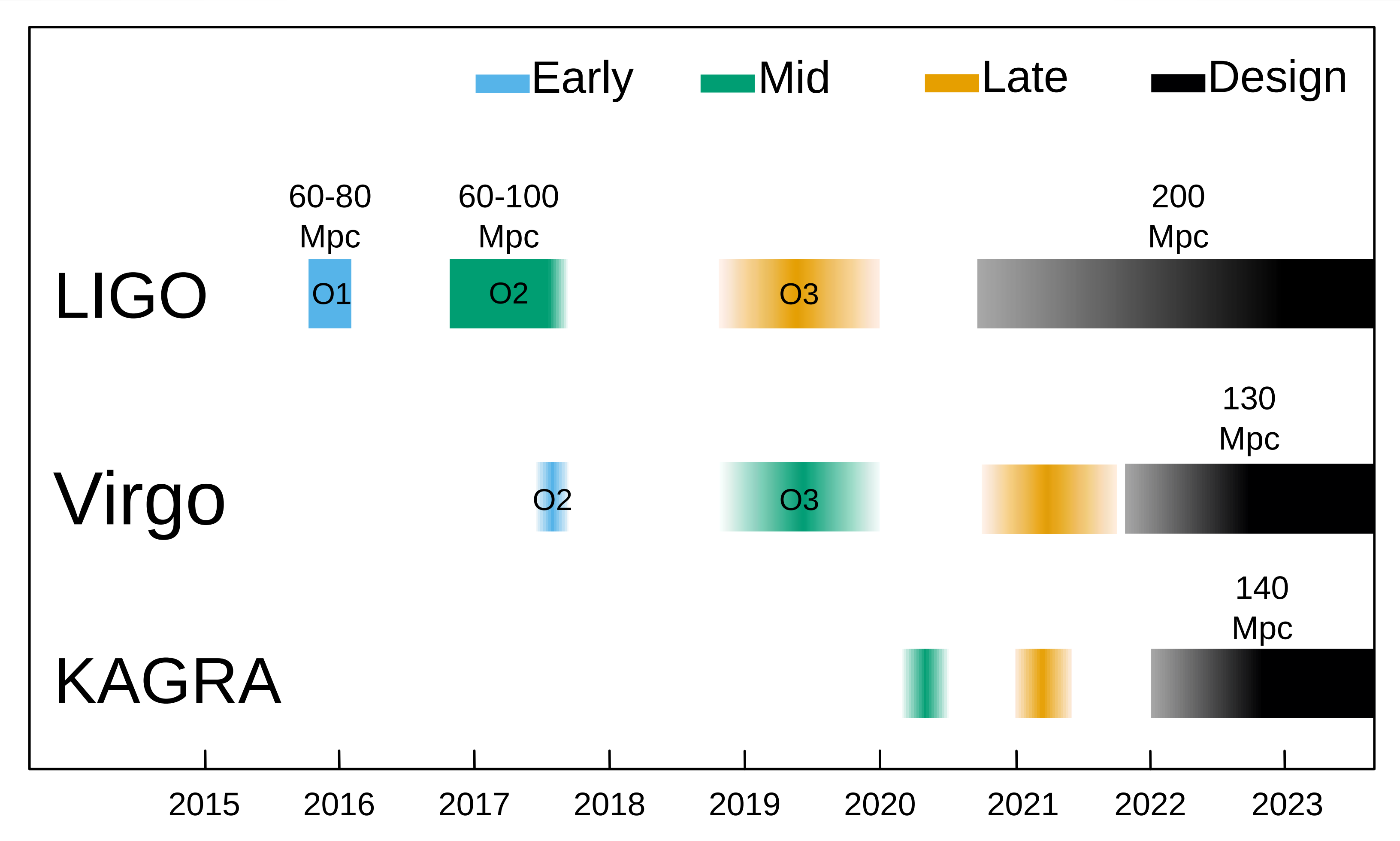
LIGO and Virgo in the next years

- Upgrade plans on LIGO and Virgo interferometers since September
- Next data taking will start in autumn 2018
- ~ one year of data taking





Observing scenario



Futur is bright !

- Expect more observations in the next runs
- More detectors will also join the LIGO-Virgo network
- We just start to uncover a complete new field
- New multi-messengers instruments around 2020 !

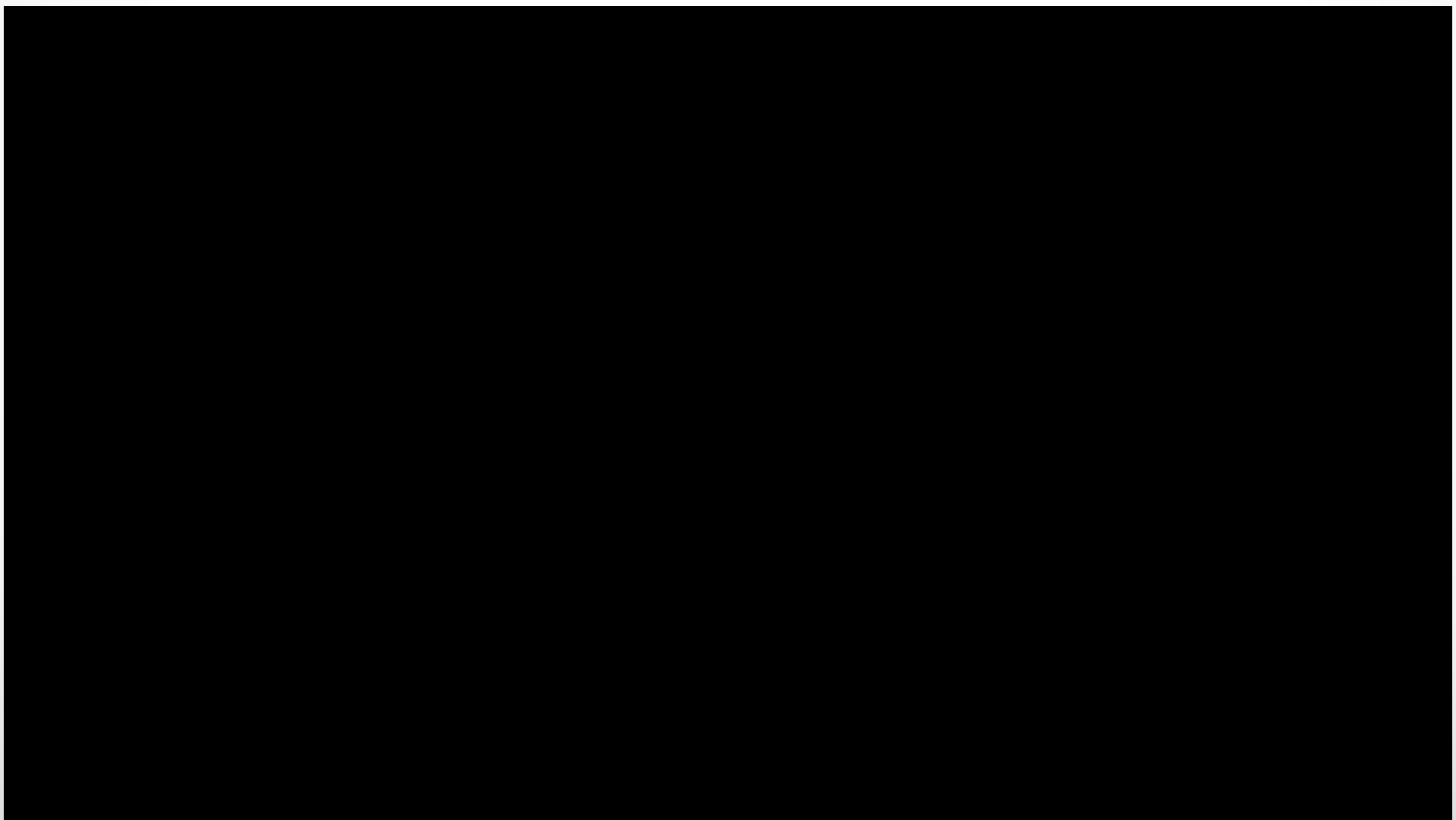


Image Credit: NASA Goddard Space Fight Center / CI Lab

backup

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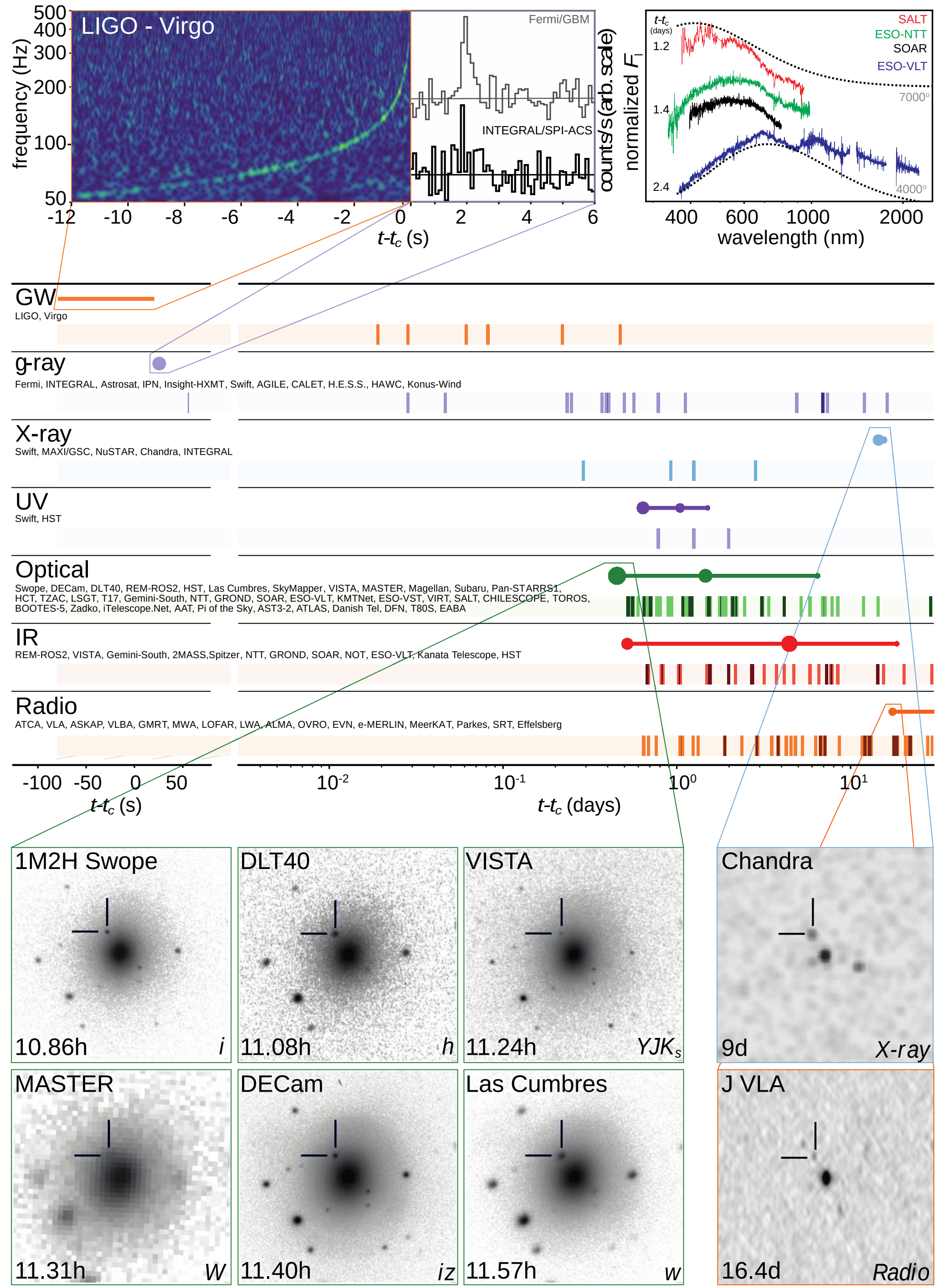
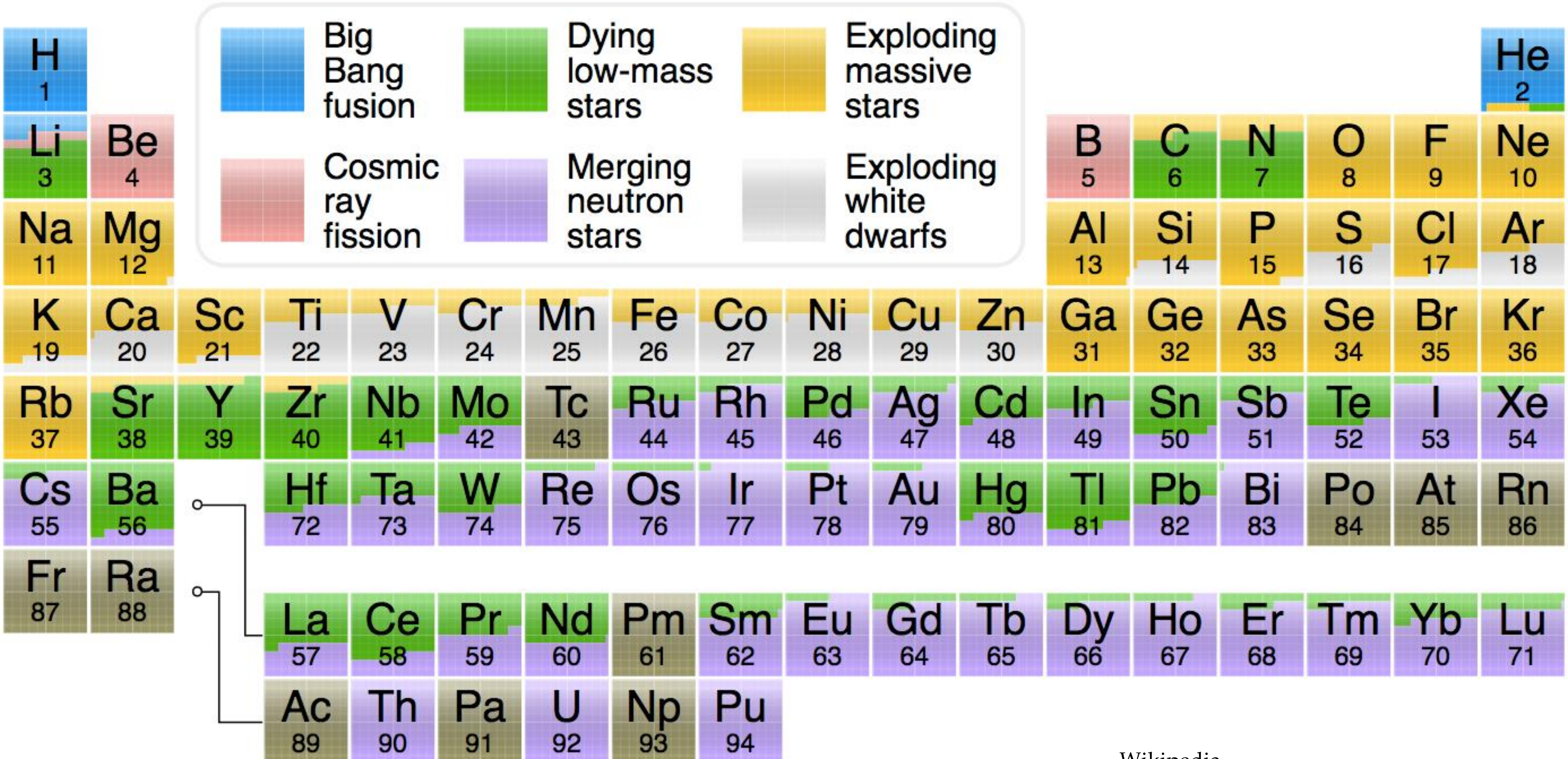
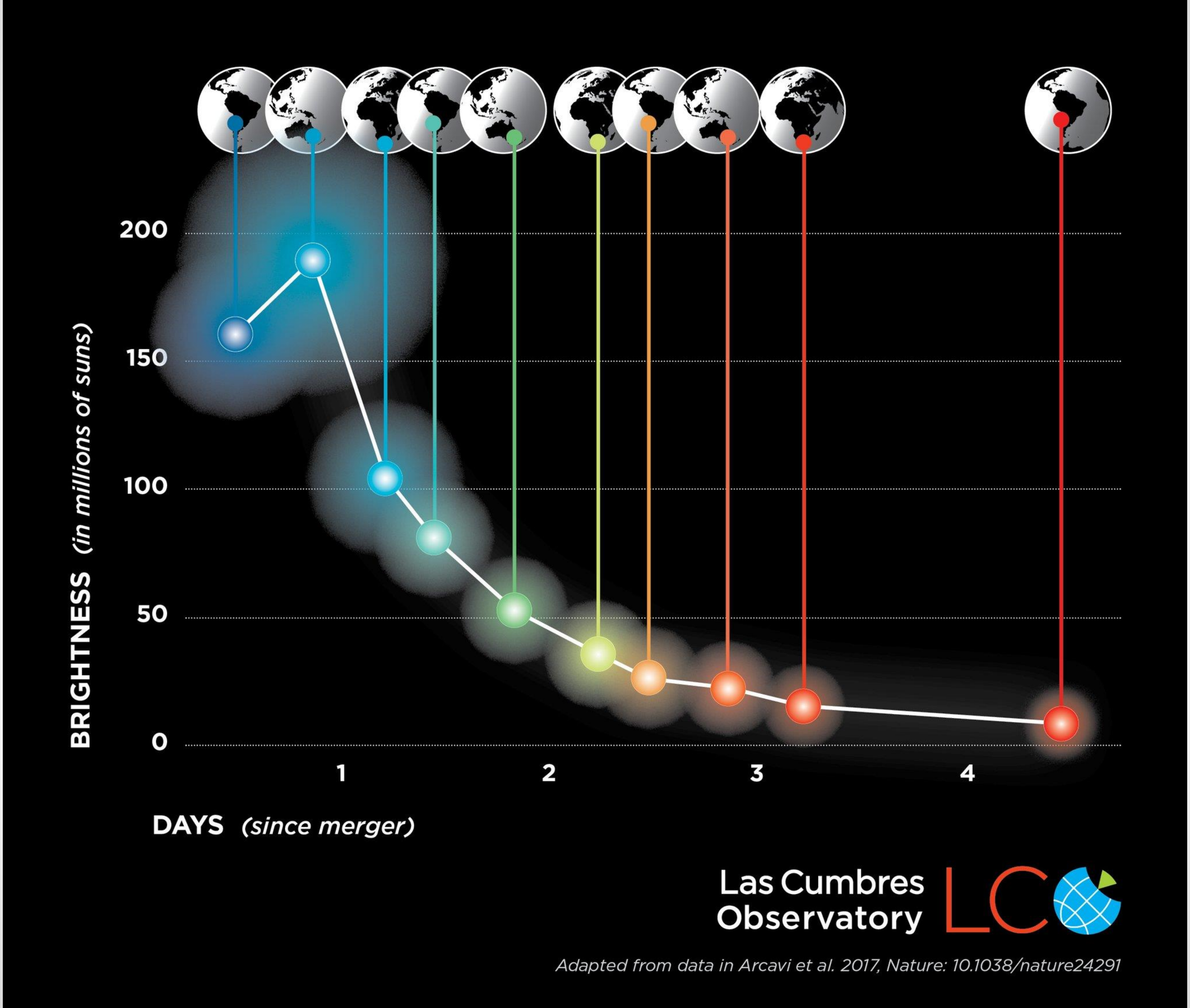
The full campaign (up to now)



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


Big Bang fusion
Dying low-mass stars
Exploding massive stars
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94

Wikipedia


200
150
100
50
0
BRIGHTNESS (in millions of suns)
1
2
3
4
DAYS (since merger)
Las Cumbres Observatory
LC
Adapted from data in Arcavi et al. 2017, Nature: 10.1038/nature24291