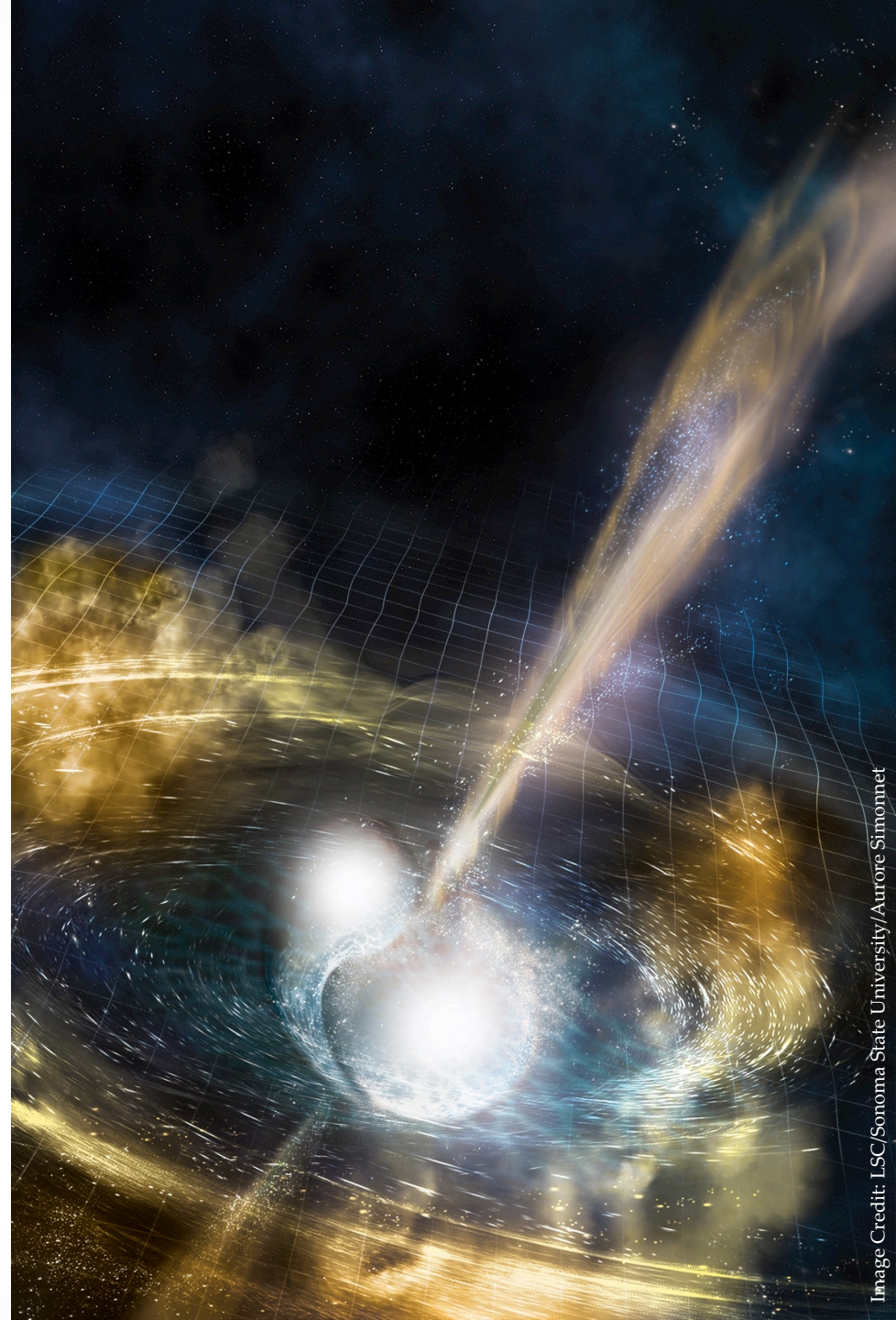




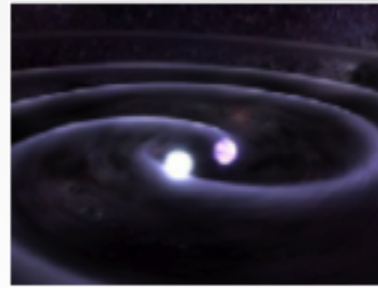
Ondes gravitationnelles : 2017, un excellent cru

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

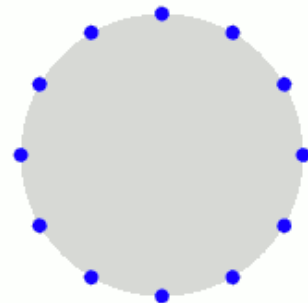
Nicolas Leroy
Laboratoire de l'accélérateur linéaire
20 novembre 2017



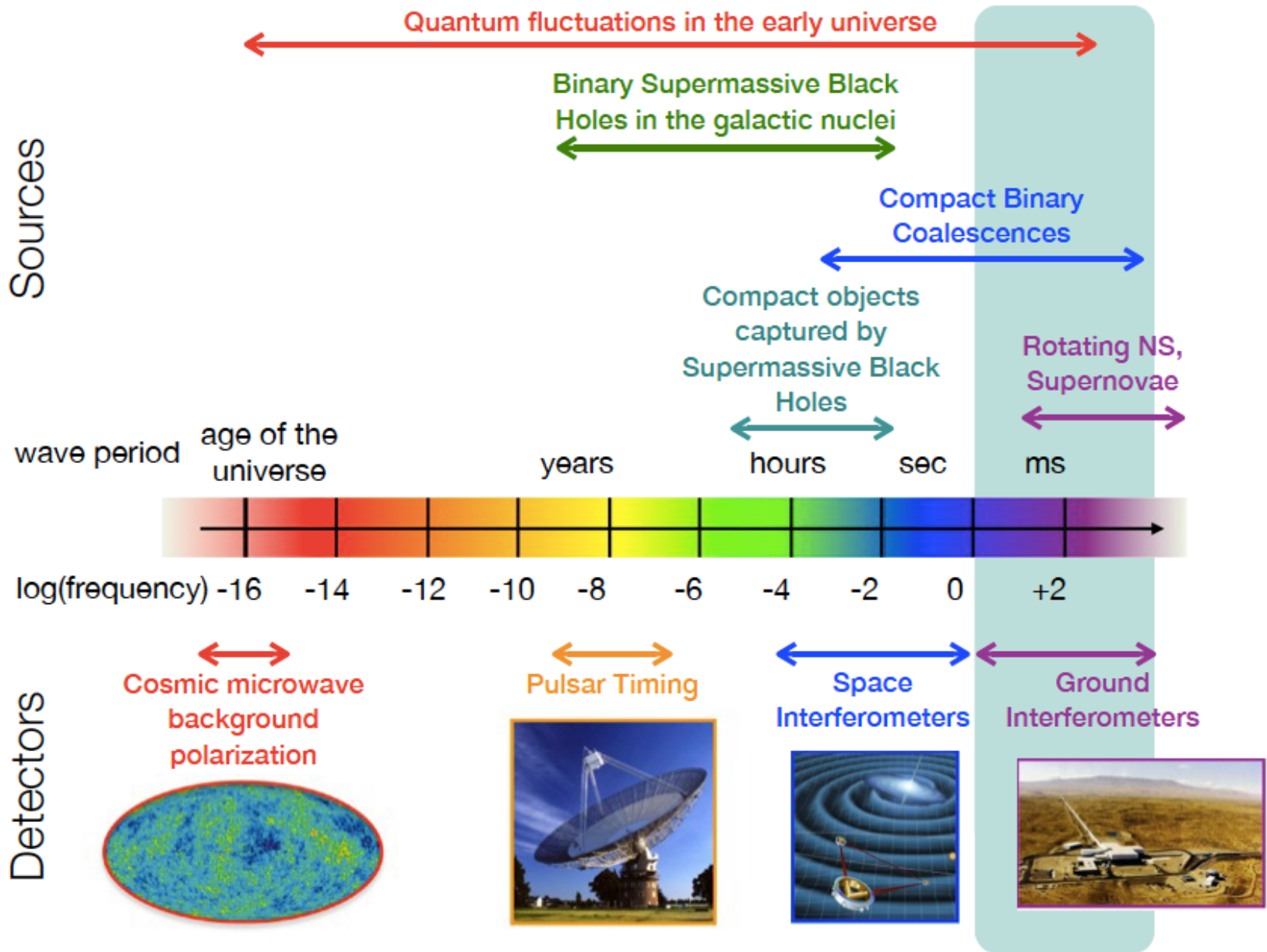
What are Gravitational waves ?



- 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 properties:
 - 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



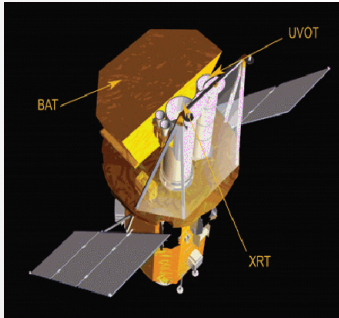
[Inspired from <http://science.gsfc.nasa.gov/663/research/>]

Multimessenger astronomy

Gamma-rays



X-rays

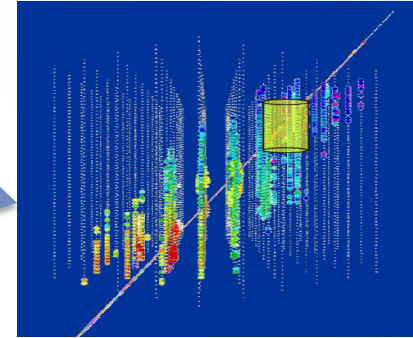


Optical



GRB

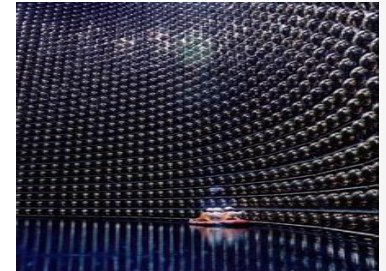
HE (>1 TeV) ν



SGR/AXP

Supernovae
type II

LE (MeV) ν



Giant Flare

Pulsar/
pulsar glitches



Radio

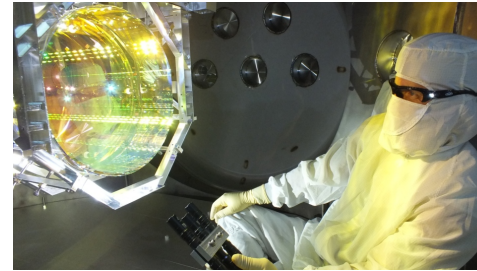
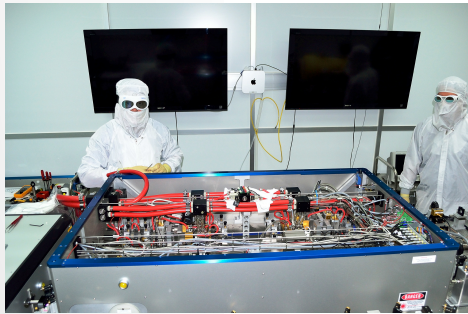
Advanced generation detectors

Michelson interferometer

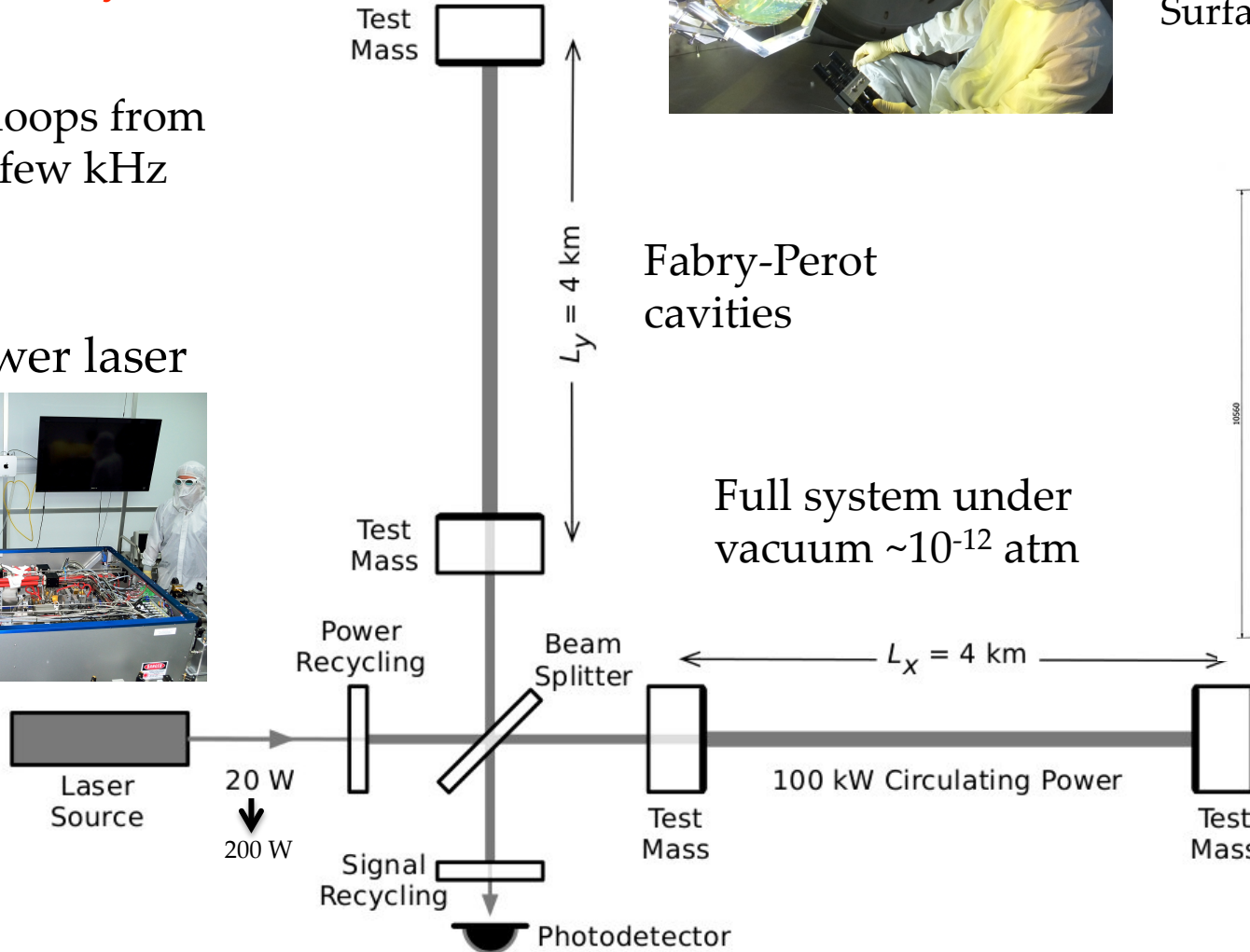
Goal : $(L_x - L_y) / L_x = 10^{-23}$

Feedback loops from few Hz to few kHz

High power laser

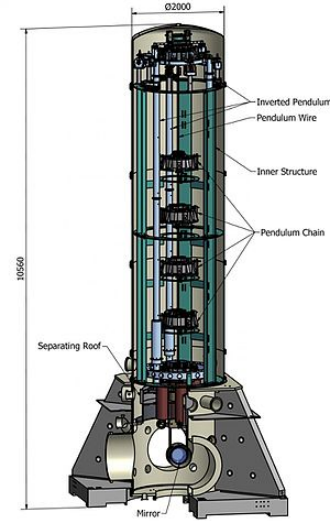


High quality optics – 40 kg
Surface RMS ~nm



Fabry-Perot cavities

Full system under vacuum $\sim 10^{-12}$ atm



Suspended Optics

Attenuation 10^{14} @ 10 Hz

The GW detectors networks

LIGO –
Hanford 4-km



GEO 600m



Virgo 3-km



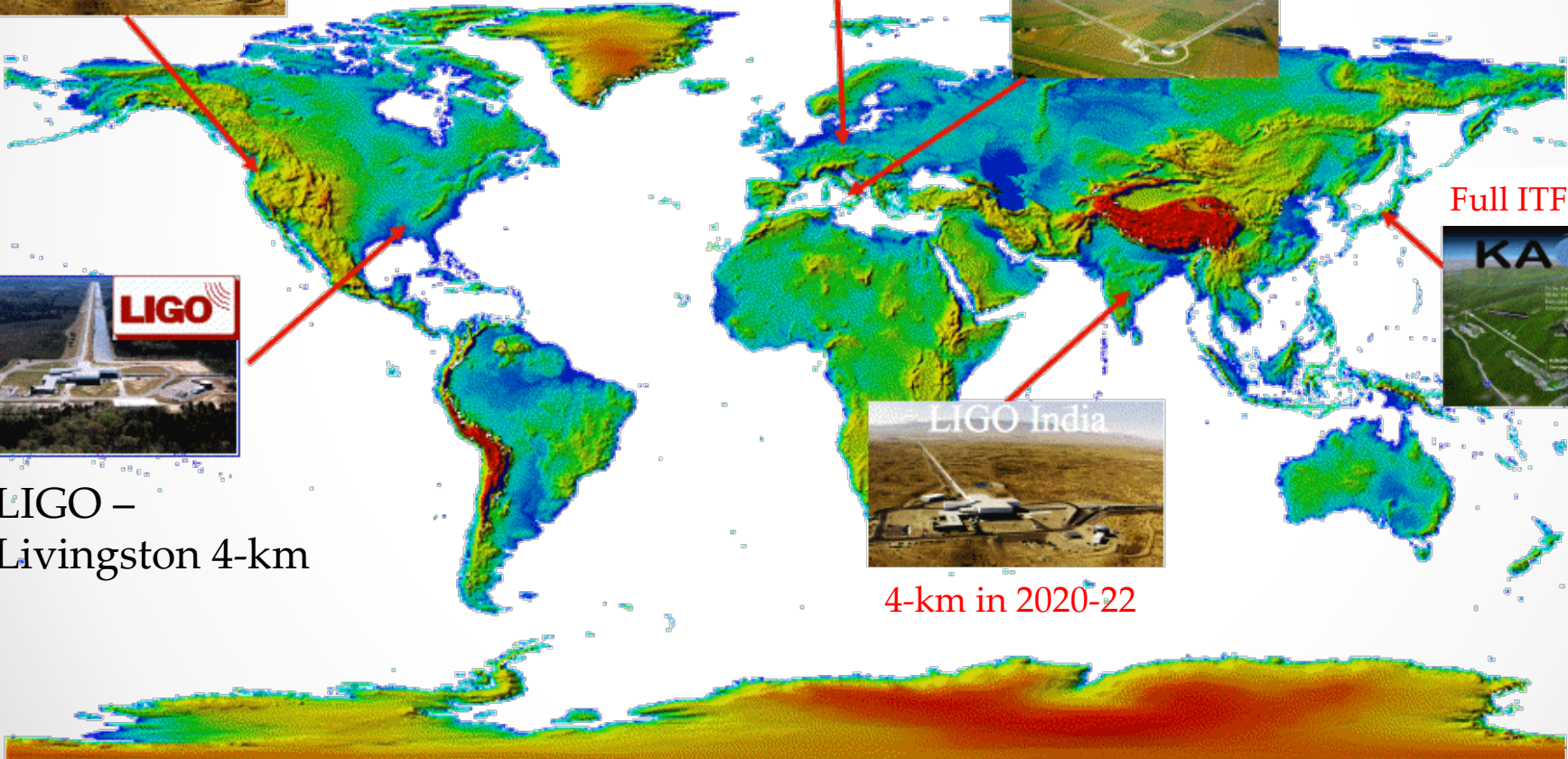
Full ITF in 2020



LIGO –
Livingston 4-km

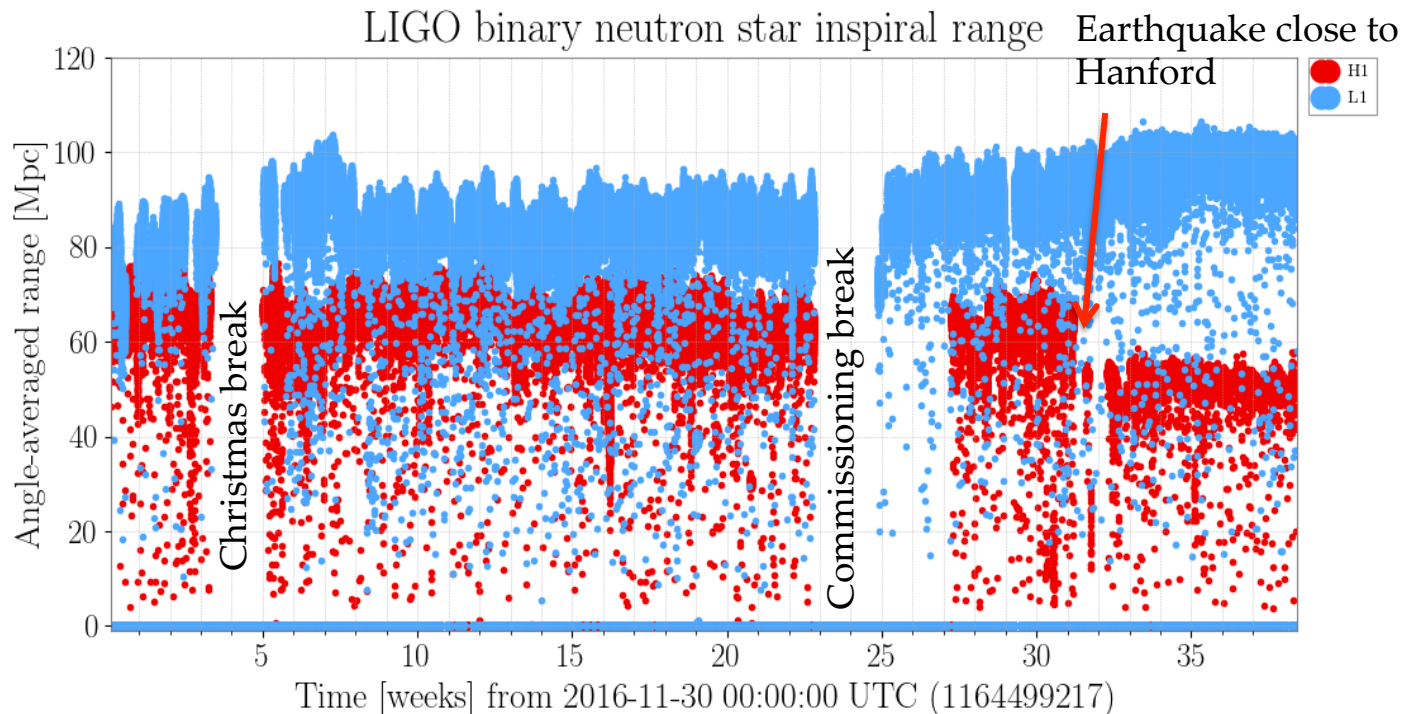


4-km in 2020-22



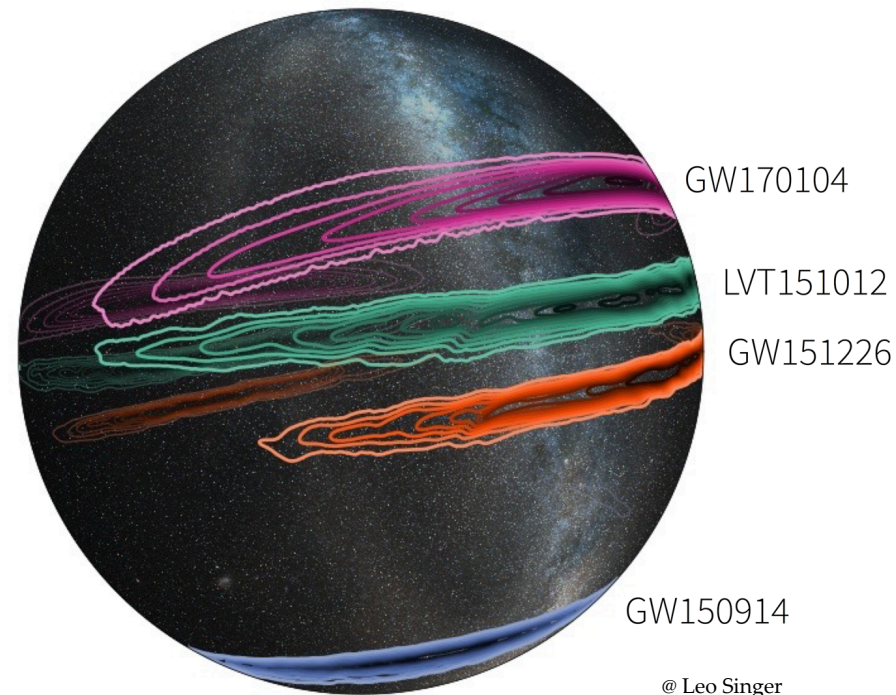
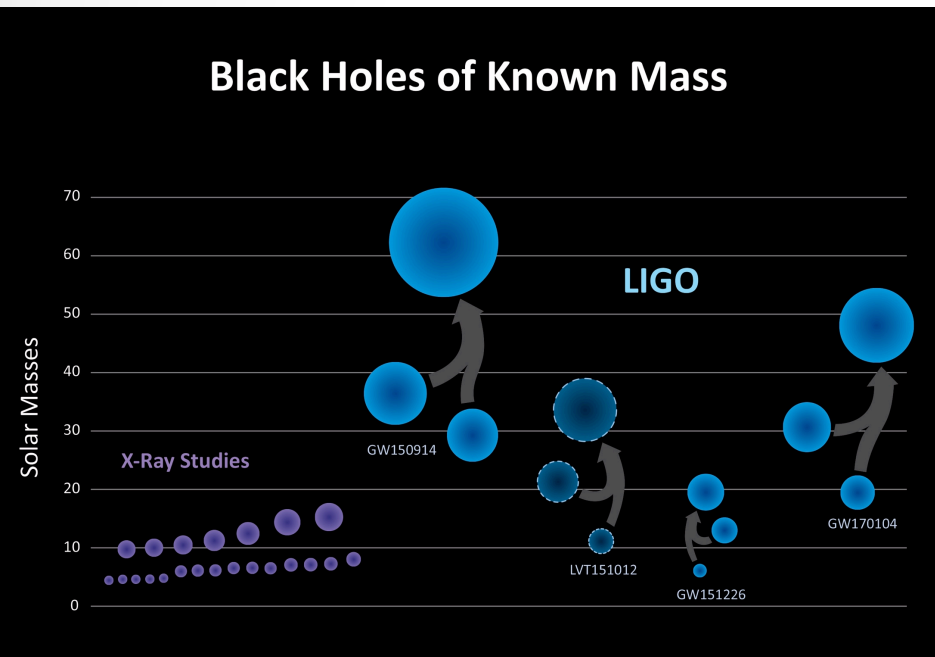
O2 run

- 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



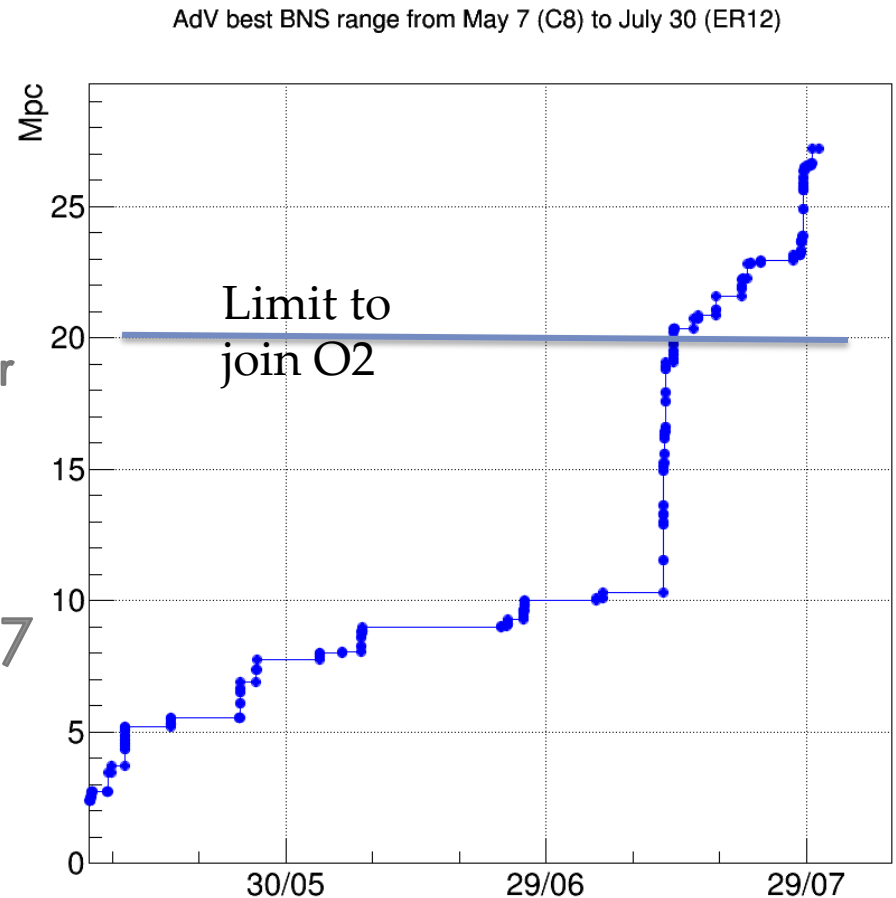
Detections after January 2017

- Binary black hole with large sky localisation



Virgo : from commisioning to scientific run

- Lock Fabry-Perot cavities : summer 2016
- Problem with monolithic suspensions
 - Move towards steel wires, complete interferometer available in December 2016
- Lock on dark fringe : February 2017
- One hour lock in March 2017
- Solve electronics problem mid July 2017
- Join O2 August 2017

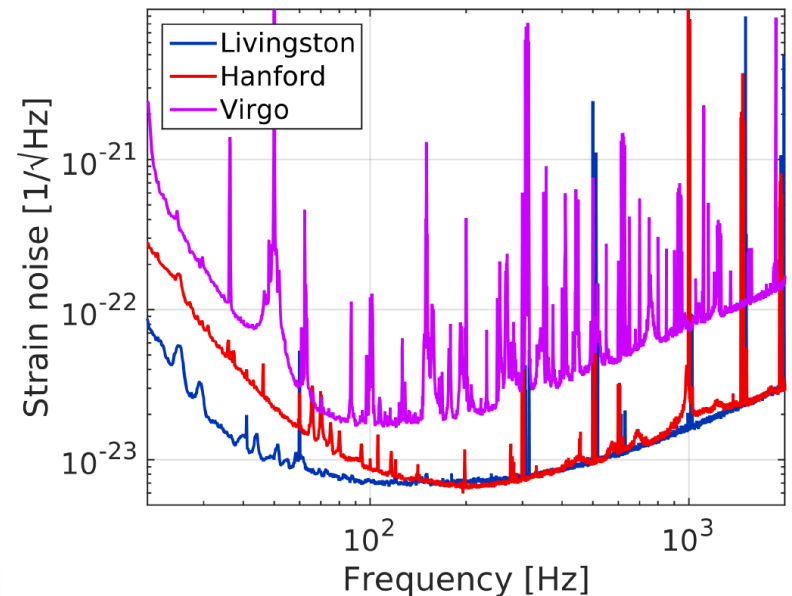
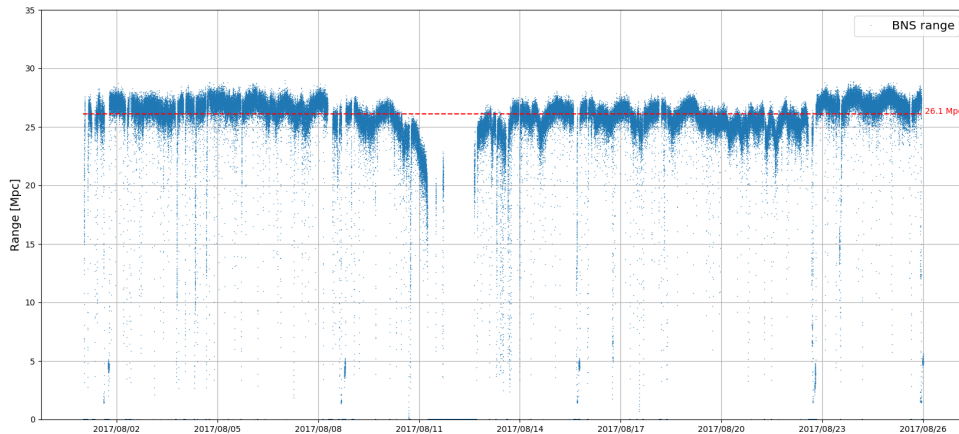


August 2017

an interesting summer

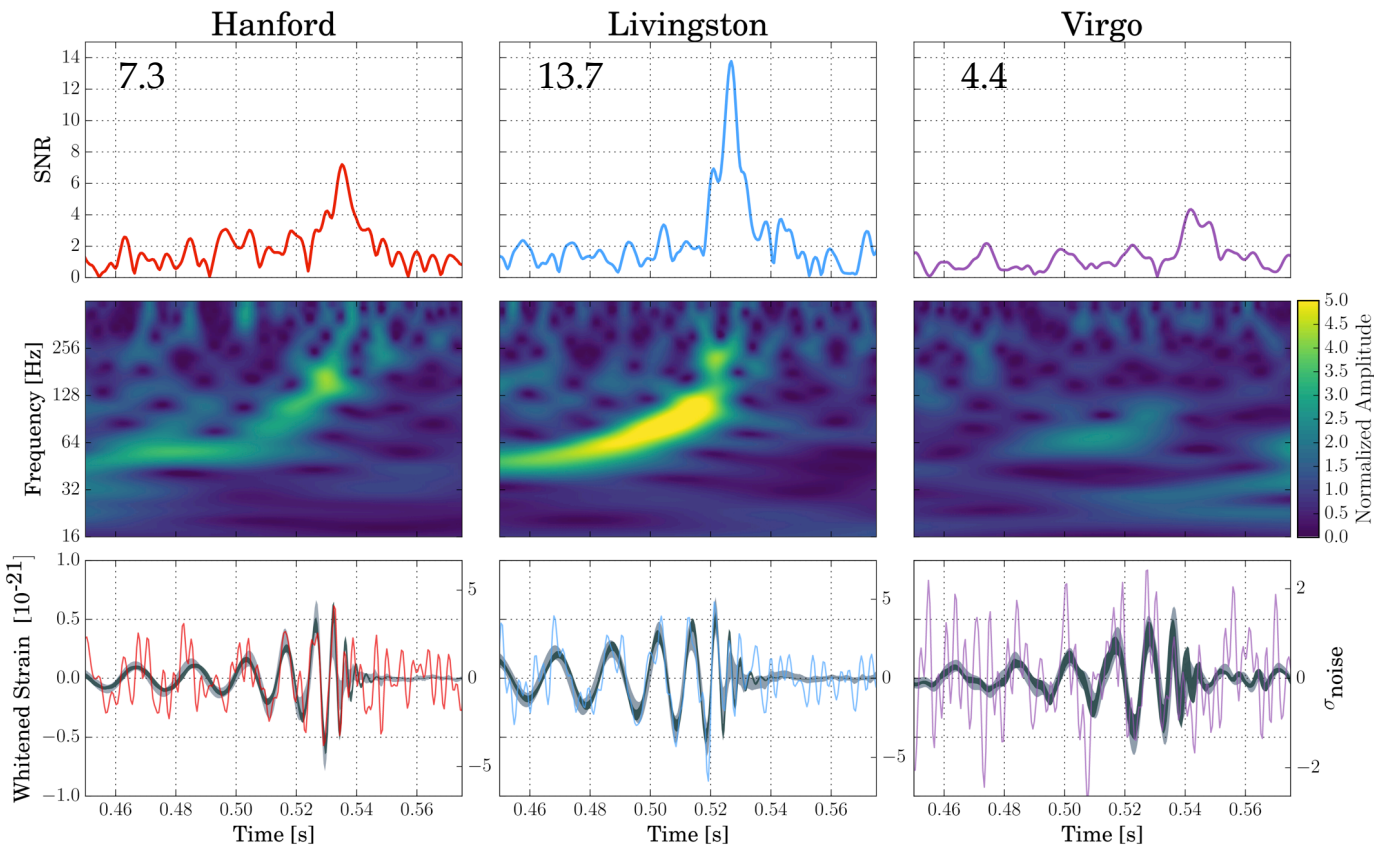
- Virgo joined August 1st 2017 for 25 days
- Duty cycle in triple coincidence ~60 %
 - Livingston : 77.6 %
 - Hanford : 75.8 %
 - Virgo : 82.4 %
- Several alerts sent during that month

Virgo BNS range: 2017/08/01 -> 2017/08/25 -- now: 2017/10/05 22:24:04 UTC



GW170814 : Virgo first detection

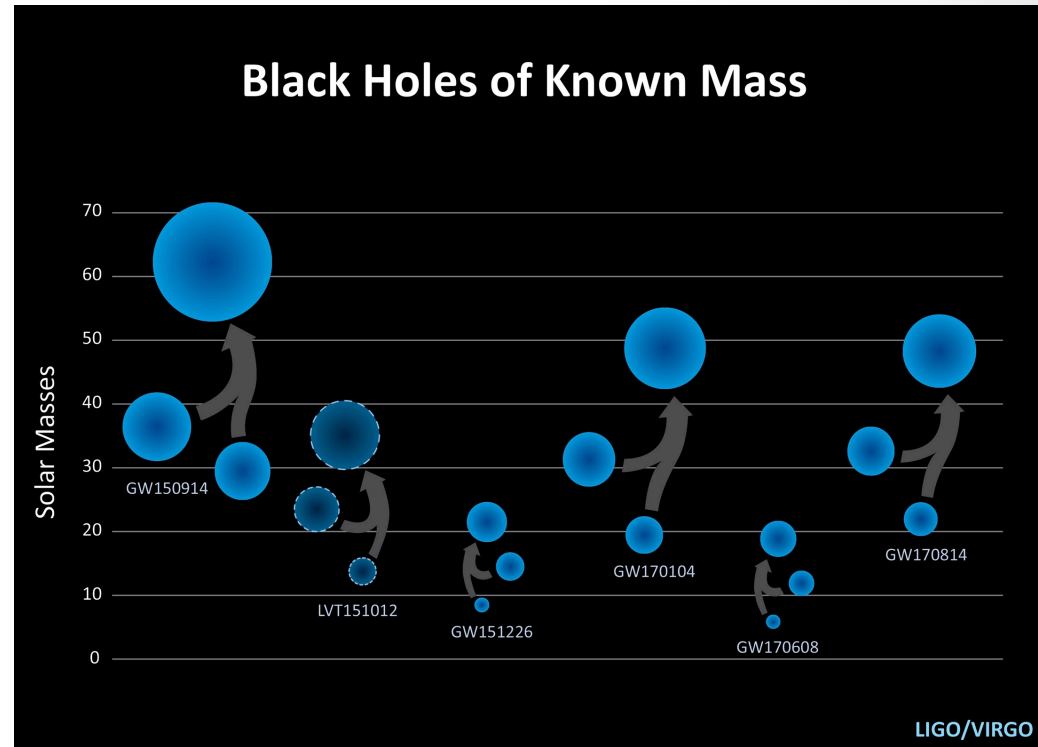
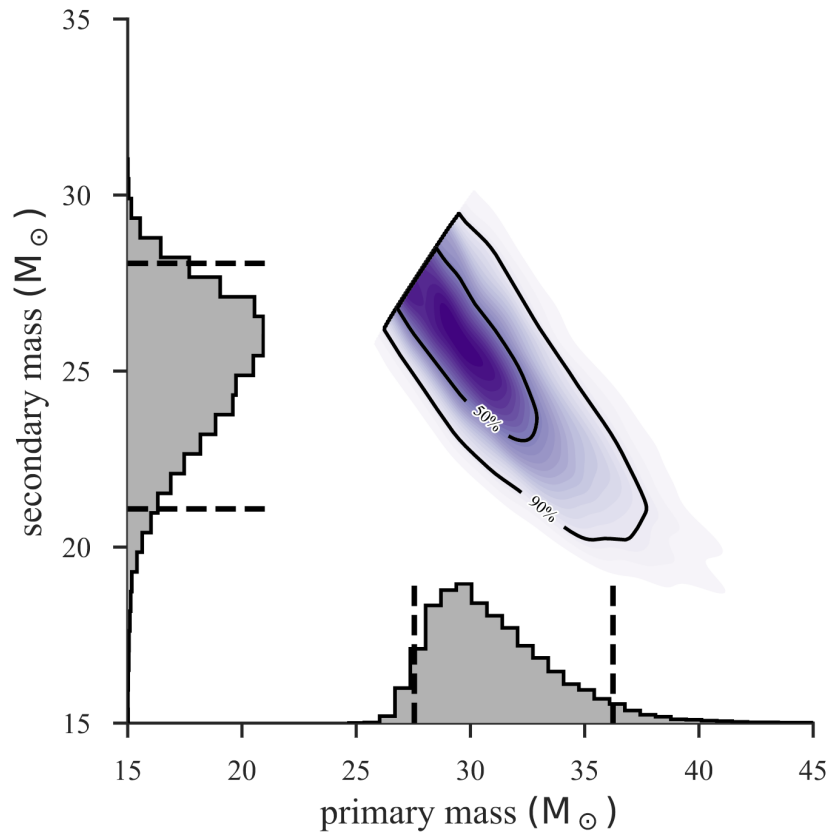
- Signal arrived at on August 14, 2017 10:30:43 UTC at Livingston, 8 ms later at Hanford, 14 ms later at Virgo;



Random chance to have signal in Virgo < 0.3 %

false alarm rate < 1 in 140,000 years

A new binary black hole



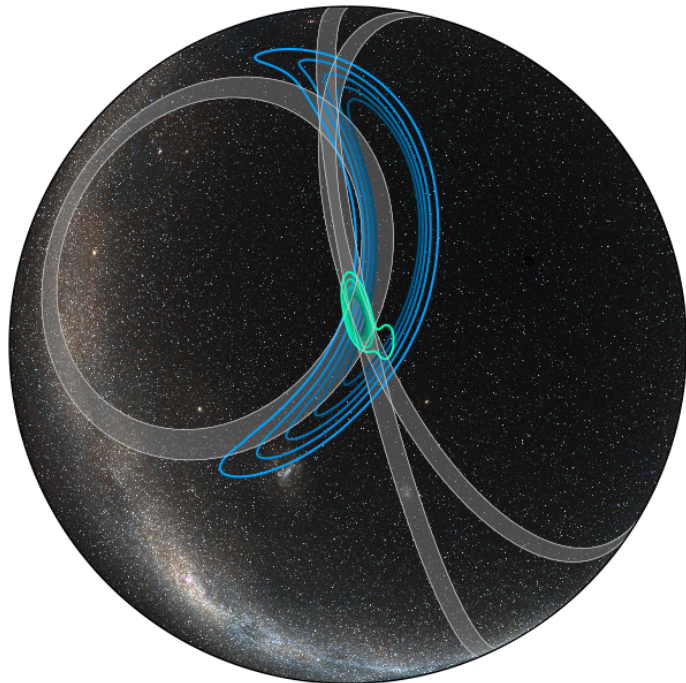
GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, Abbott *et al.*, PRL 119, 141101

Source parameters

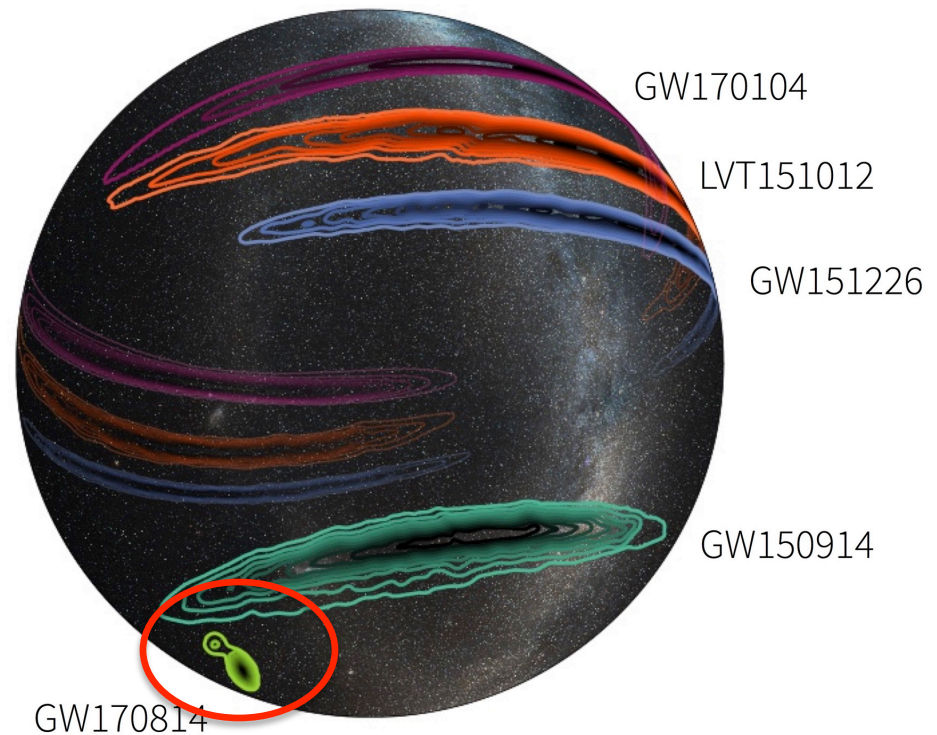
Primary black hole mass m_1	$30.5^{+5.7}_{-3.0} M_{\odot}$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2} M_{\odot}$
Chirp mass \mathcal{M}	$24.1^{+1.4}_{-1.1} M_{\odot}$
Total mass M	$55.9^{+3.4}_{-2.7} M_{\odot}$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5} M_{\odot}$
Radiated energy E_{rad}	$2.7^{+0.4}_{-0.3} M_{\odot} c^2$
Peak luminosity ℓ_{peak}	$3.7^{+0.5}_{-0.5} \times 10^{56} \text{ erg s}^{-1}$
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	$540^{+130}_{-210} \text{ Mpc}$
Source redshift z	$0.11^{+0.03}_{-0.04}$

Better sky localisation

(compare to LIGO only)



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



GW170104

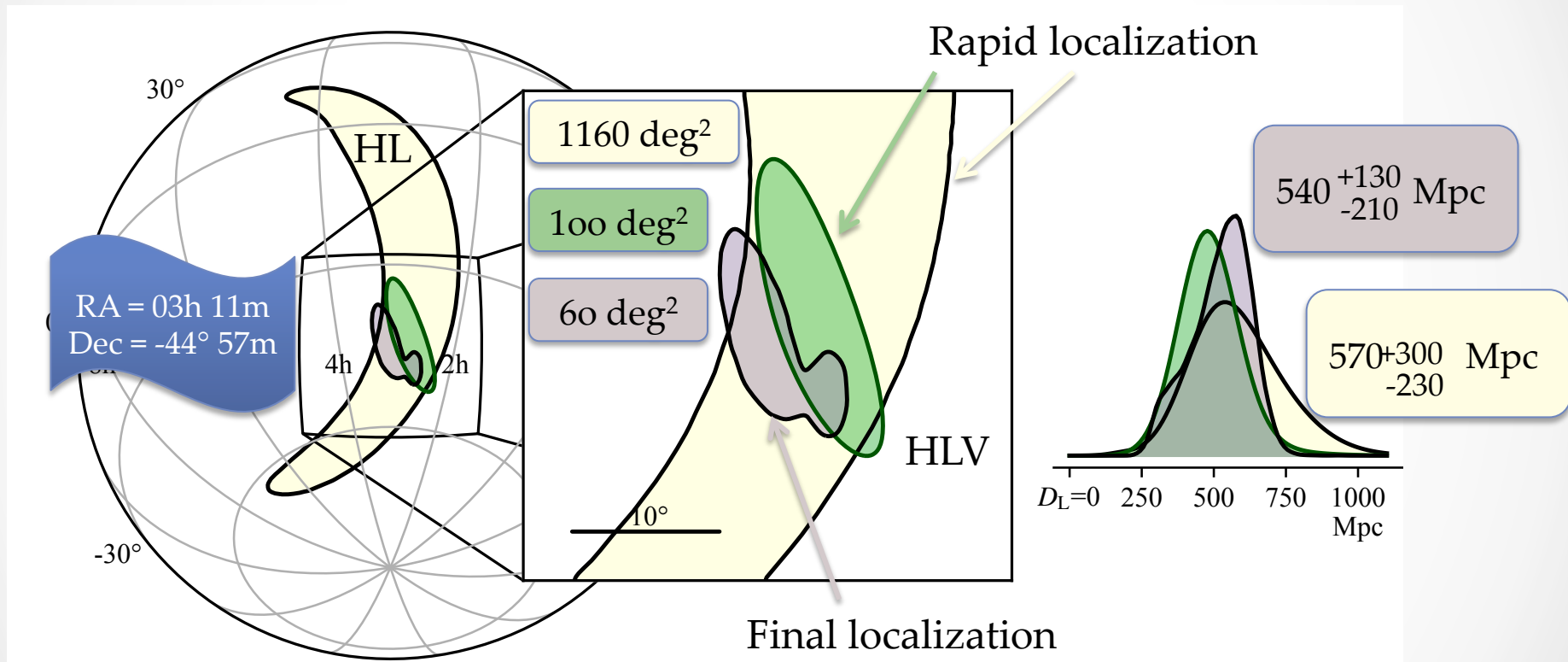
LVT151012

GW151226

GW150914

GW170814

Source parameters improvements

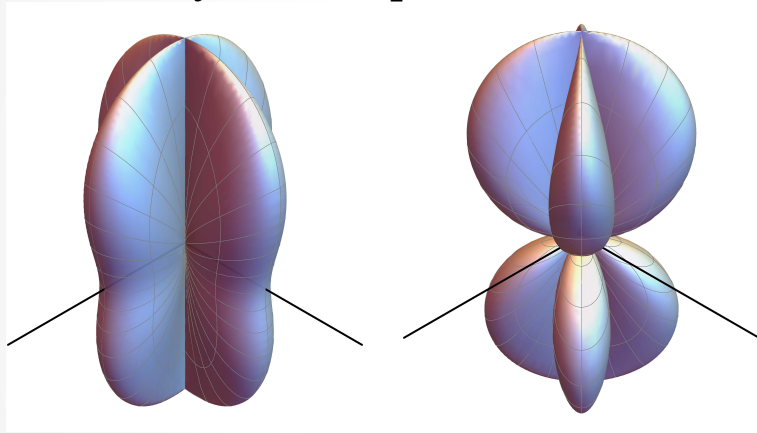


Error in sky area : factor 20 !
Reduced incertitude in distance by 1.5

Polarization in GR

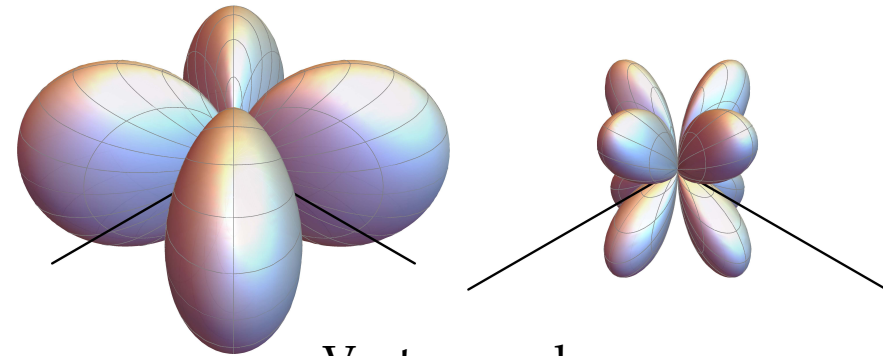
- With a third detector (non aligned) : test new types of polarization

Only ones expected with GR



Tensor modes

Allowed by other gravitation theories

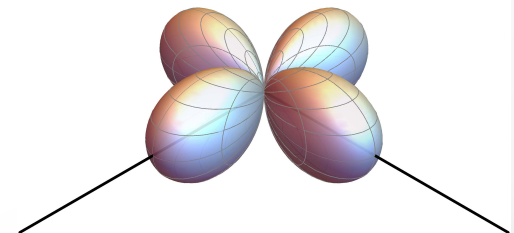


Vector modes

Antenna pattern

Favor pure tensor vs pure vector or scalar

Cannot conclude on mixed version

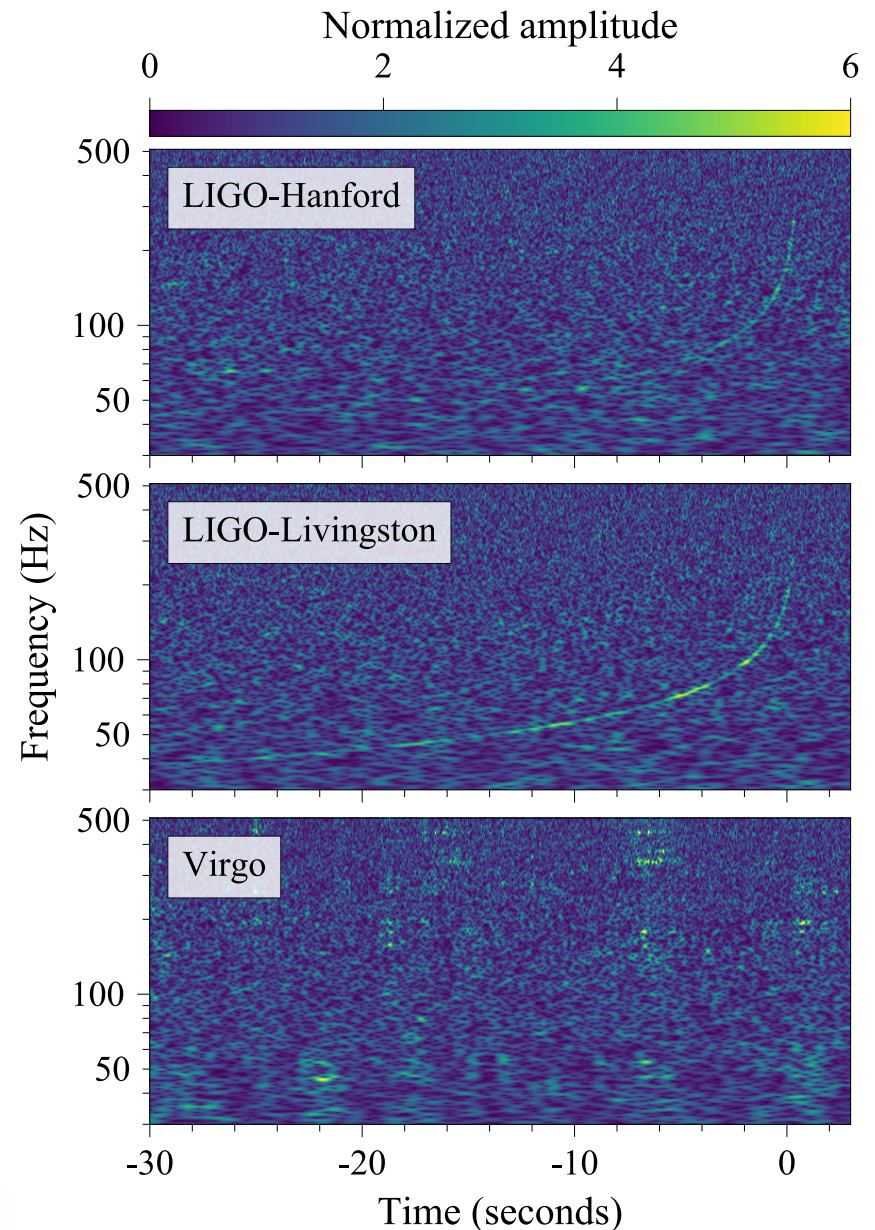
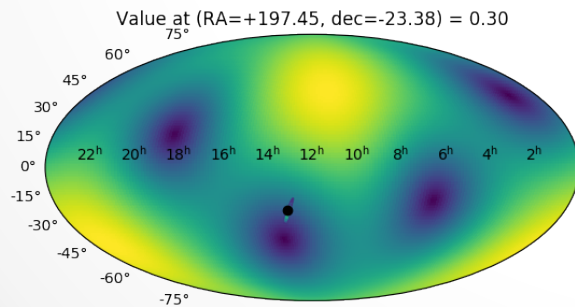


Scalar modes

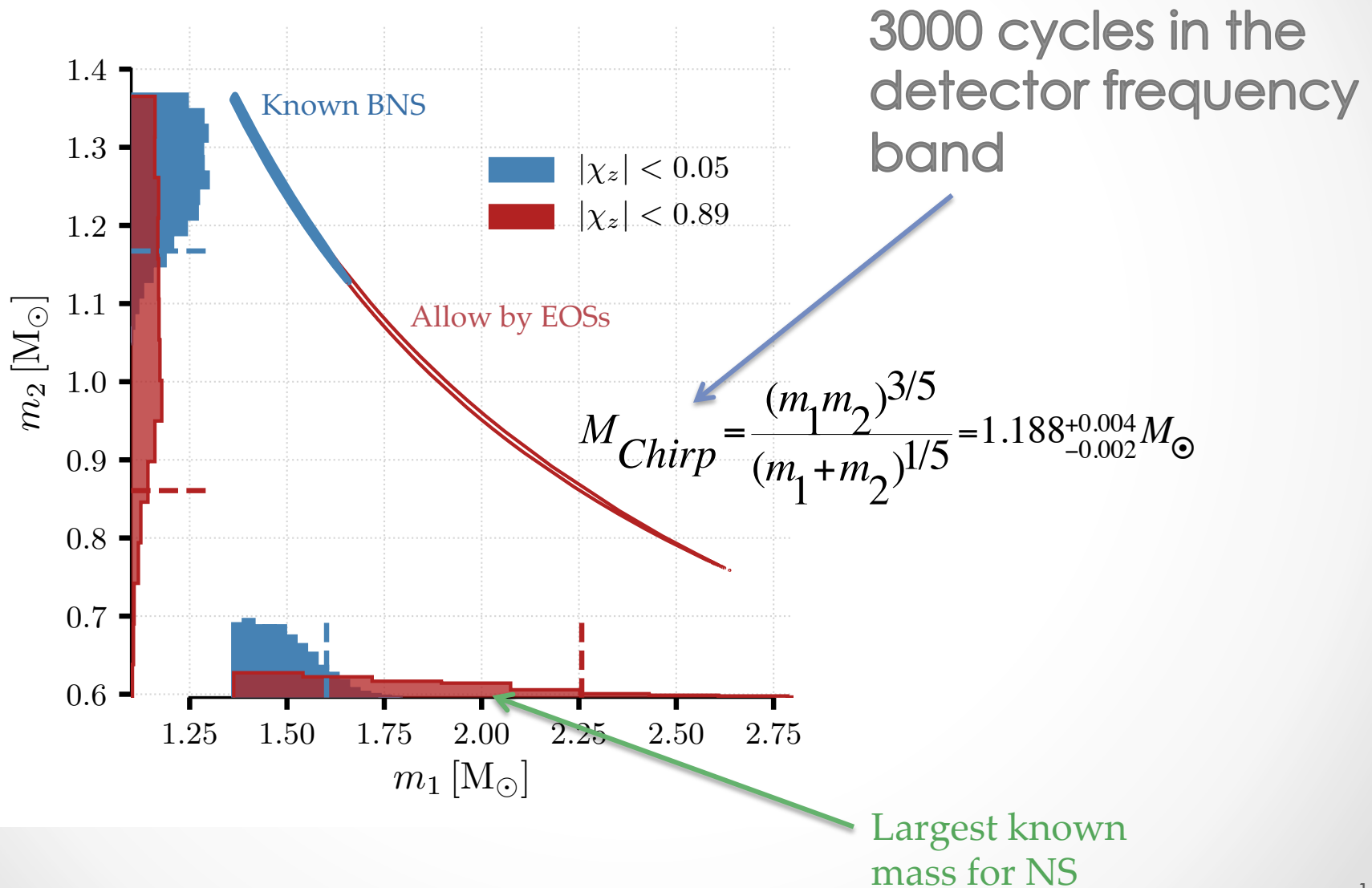
GW data

- SNR ~ 32.4 , FAR $\sim 110^{-6}$ 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

V1 beam pattern -- skymap is LALInference_r1.fits



Masses

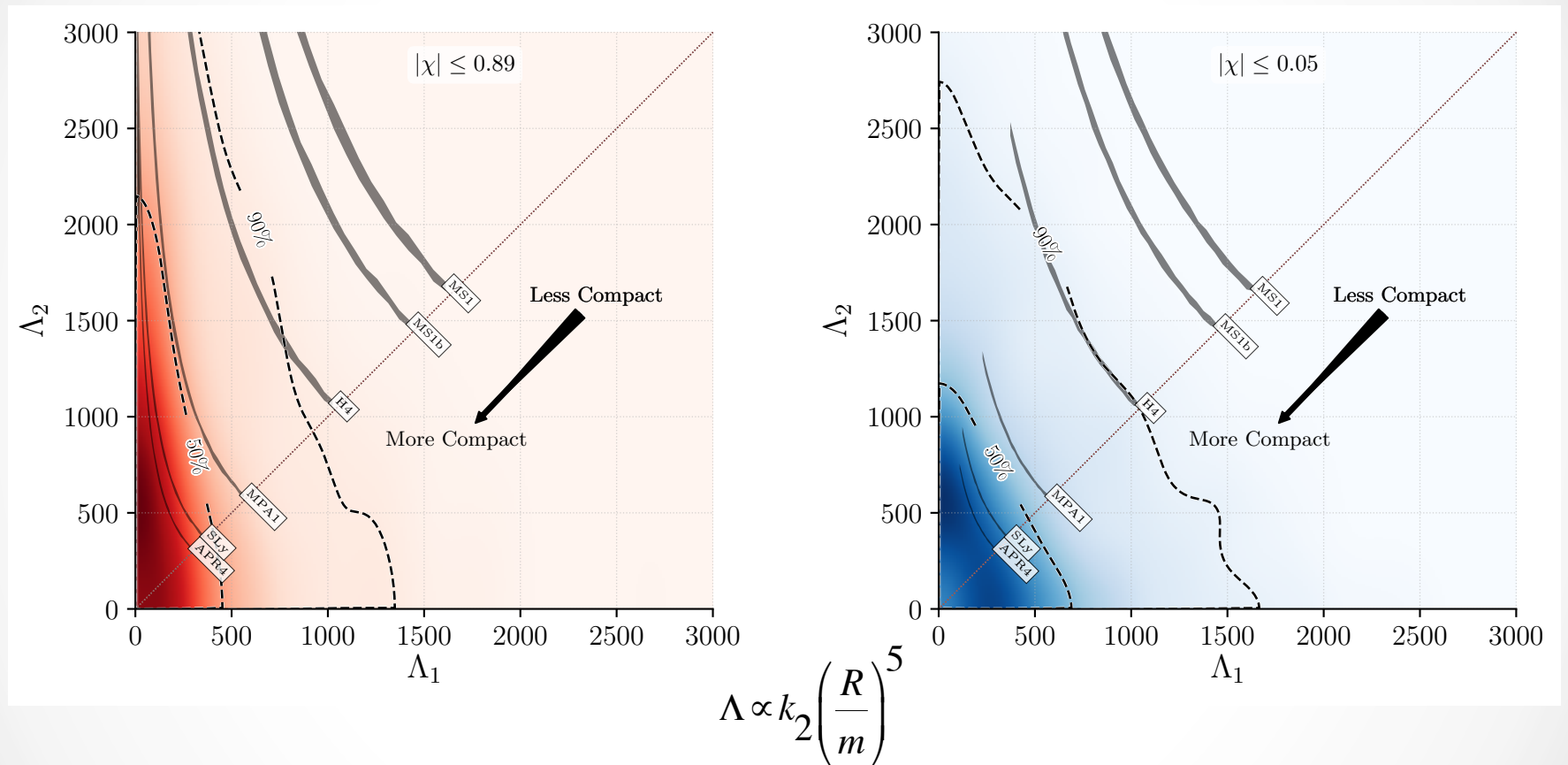


Source parameters

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

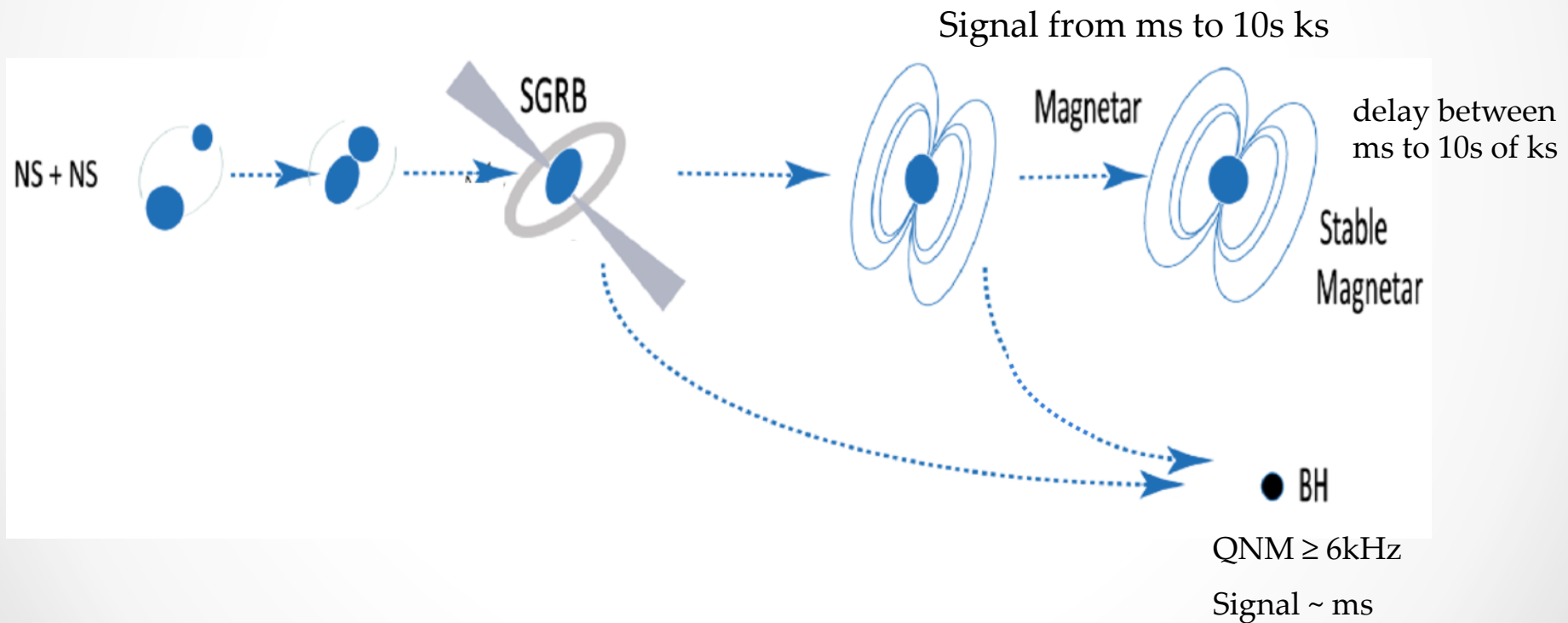
Equation of state (EOS)



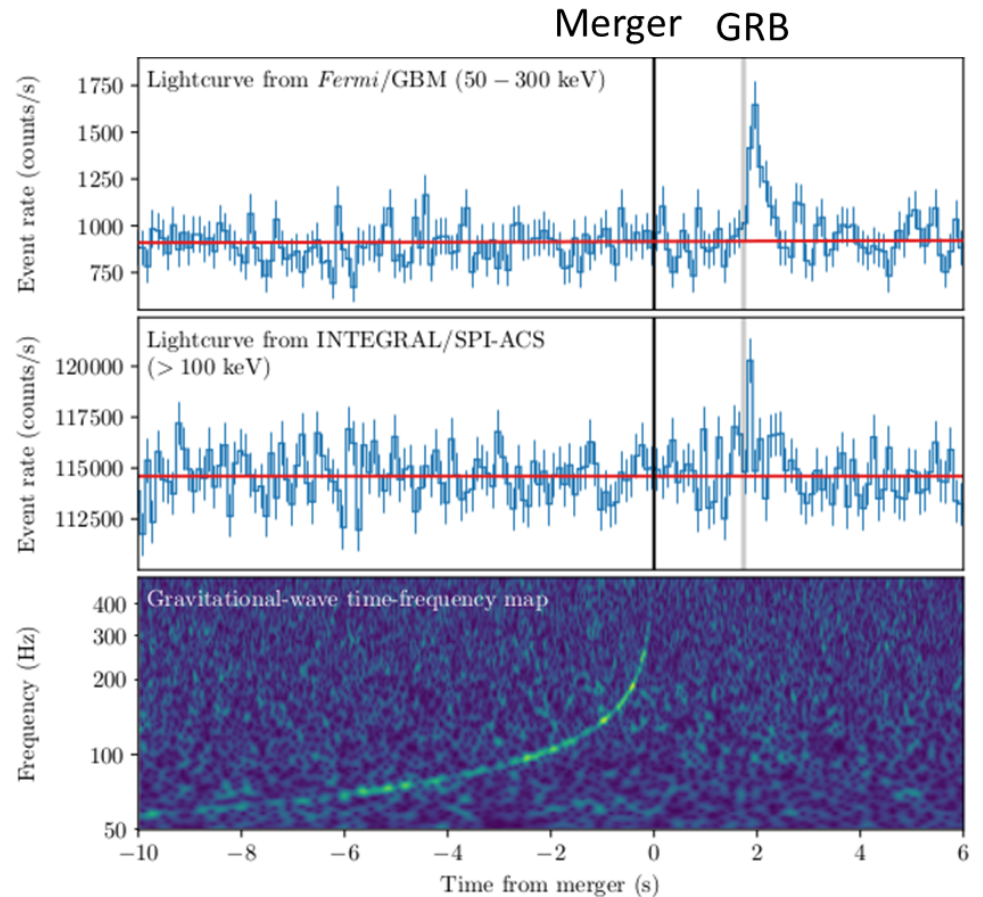
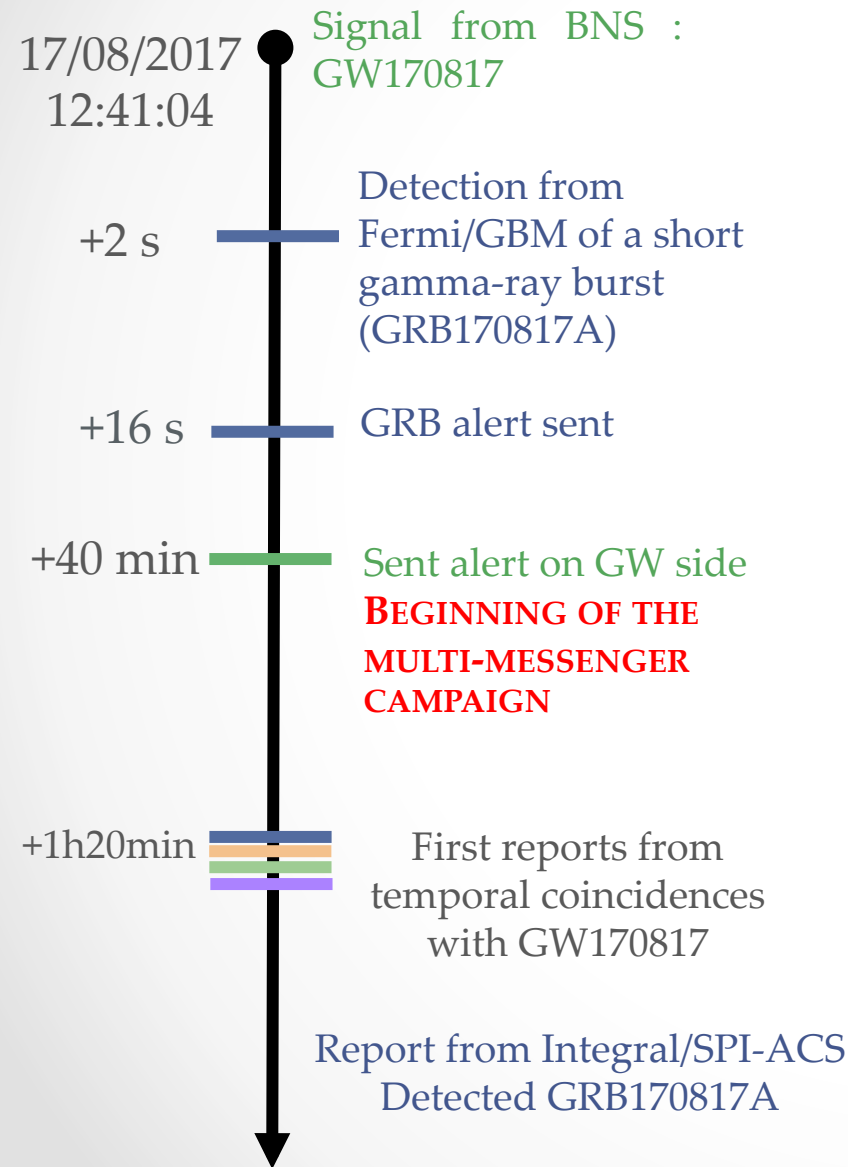
- Signal observed favour EOS for compact NS

Remanent object

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



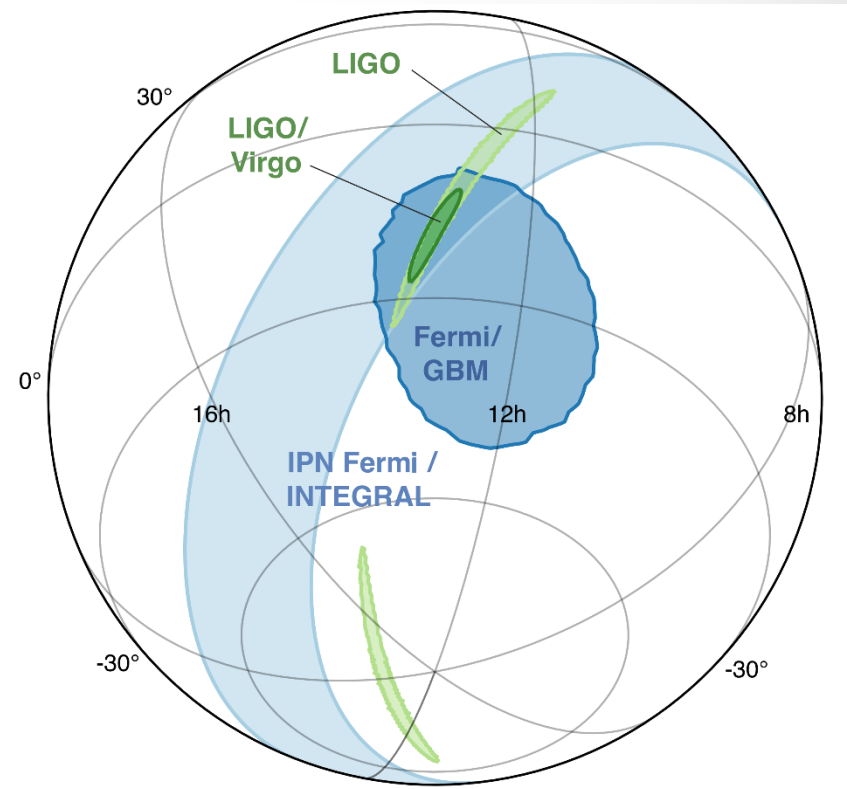
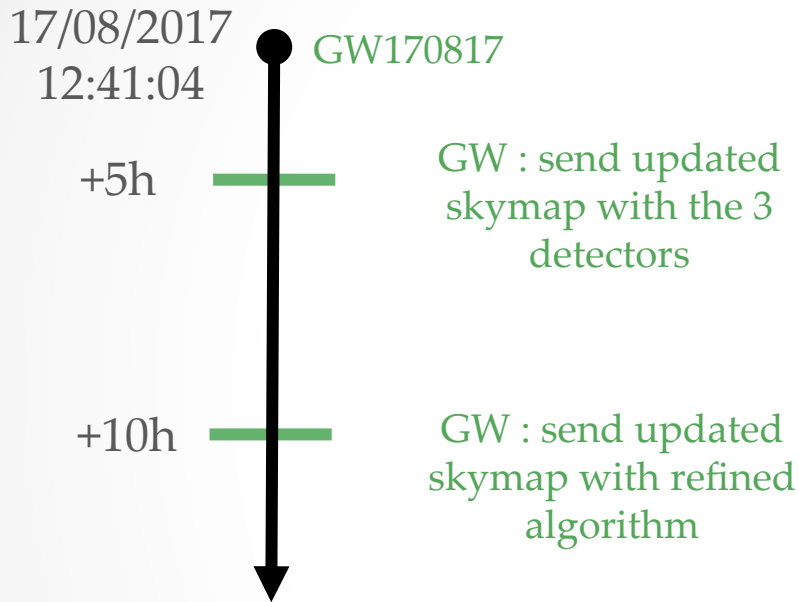
What an alert !



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

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

Key role from Virgo in the localisation



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

GW170817 localization

2 interferometers (HL)	Adding Virgo (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

+2 s

+5h

+11h

+1.2j

+9j

+16j

GW170817

GRB170817A

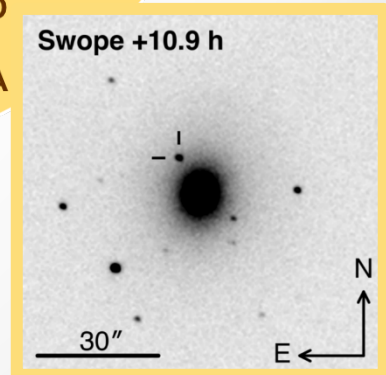
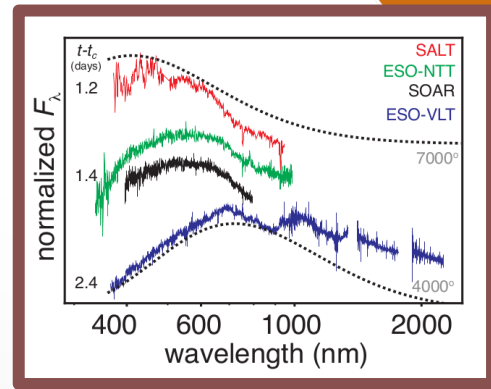
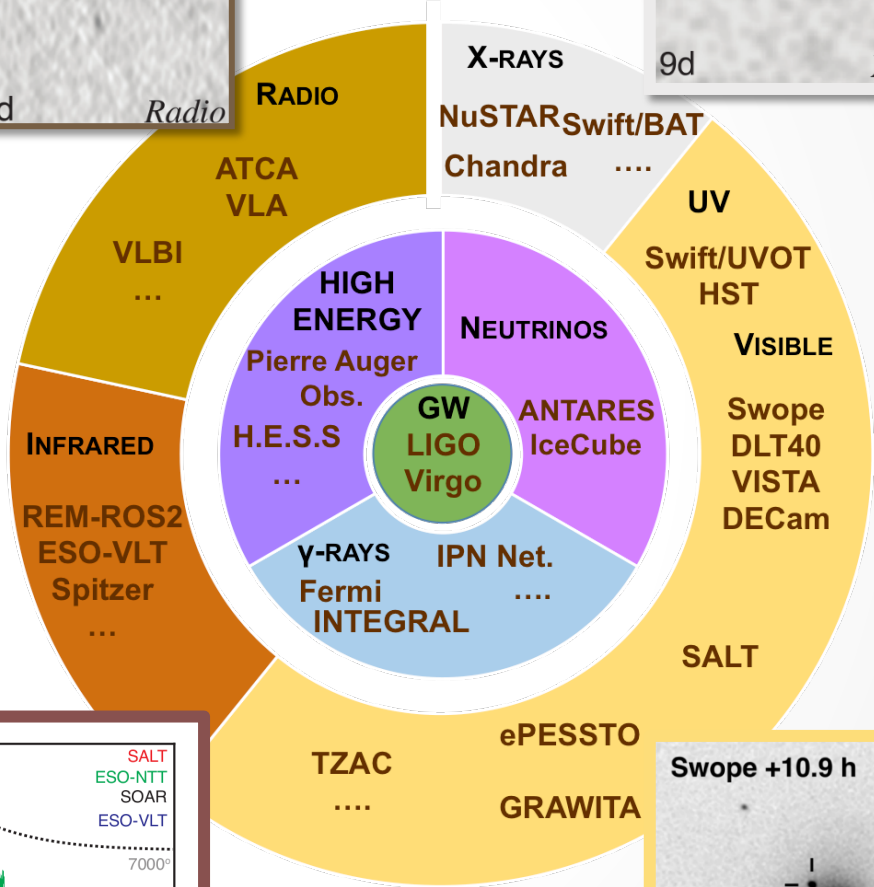
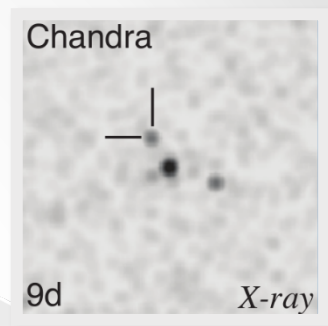
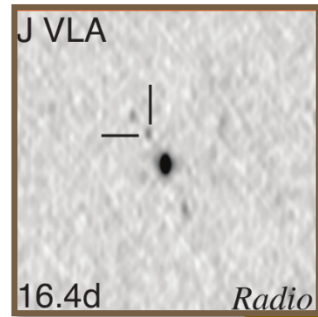
Localisation with GW
Distance 40 Mpc

Discovery of kilonova
AT2017gfo by Swope
Find host galaxy : NGC4993
START CAMPAIGN ON AT2017GFO

First spectra of the kilonova

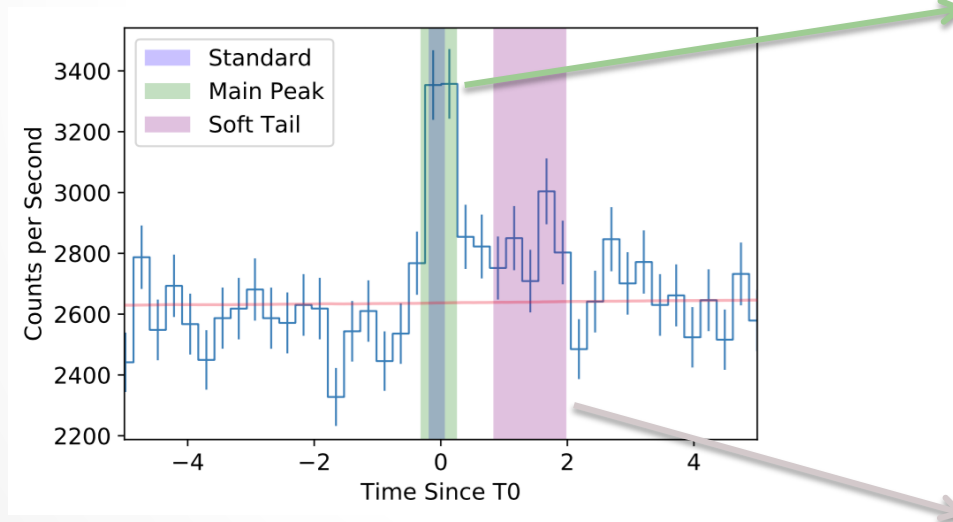
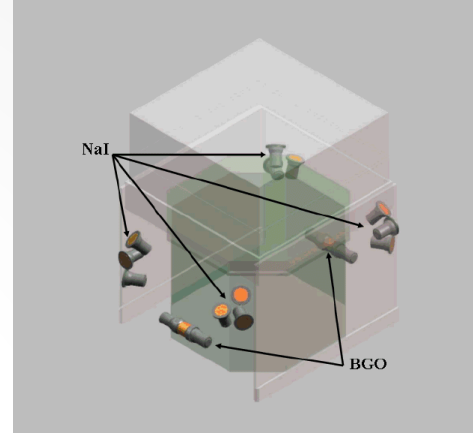
Discovery of an X-ray counterpart

First radio
signal found
with VLA

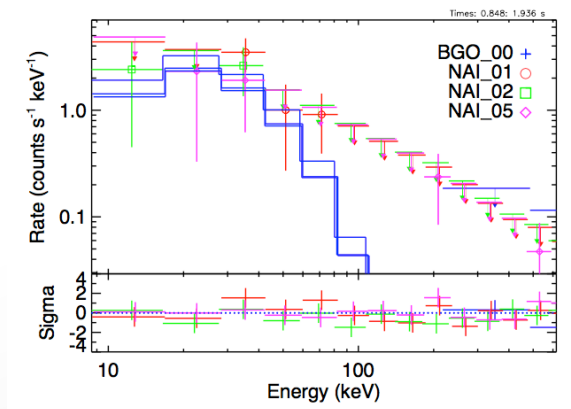
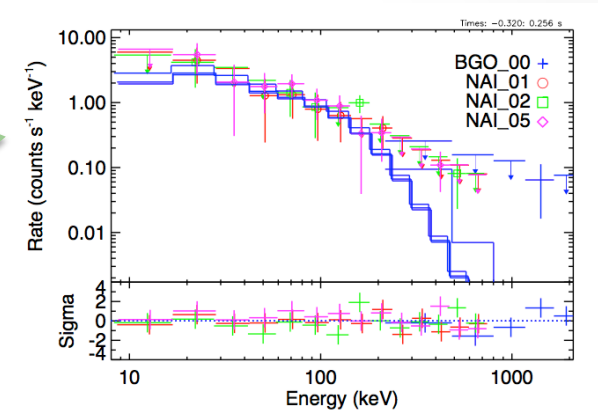


GRB detection

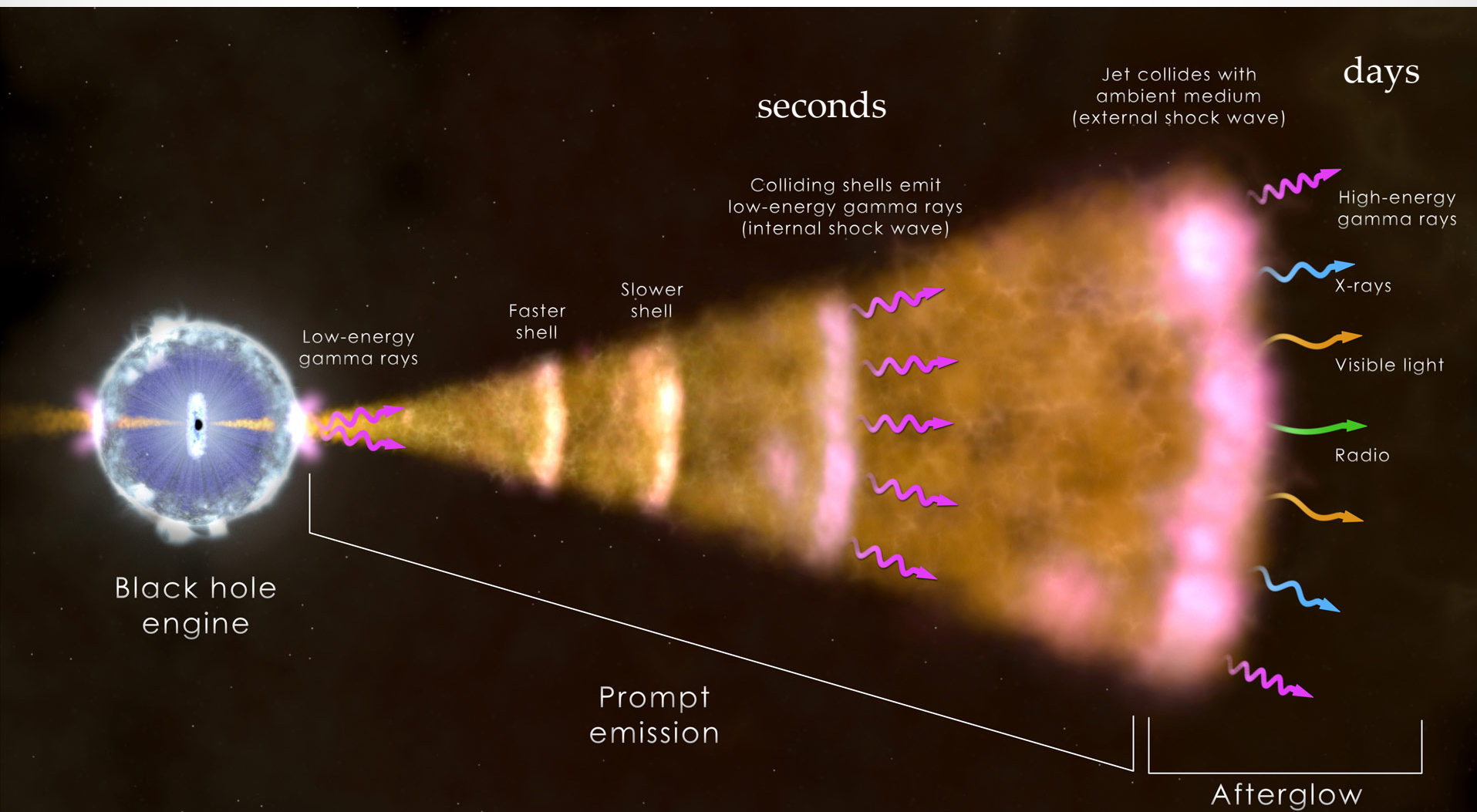
- Burst detected on board by in 3/12 GBM detectors
- Weak event $E_{\text{iso}} = 3.1 \pm 0.7 \cdot 10^{46}$ erg
- Duration : 2 ± 0.5 s – shift with GW 1.74 ± 0.05 s
- Confirmed by offline analysis using Integral/SPI-ACS



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 :
$$-3 \cdot 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq +7 \cdot 10^{-16}$$
- Equivalent principle (Shapiro effect) :
$$\delta t_s = -\frac{1+\gamma}{c^3} \int_{r_e}^{r_o} U(r(l)) dl$$

$-2.6 \cdot 10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2 \cdot 10^{-6}$
Deviation to Einstein-Maxwell

↑
gravitational potential
- Lorentz Invariance violation :

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

Common GW-GRB analysis

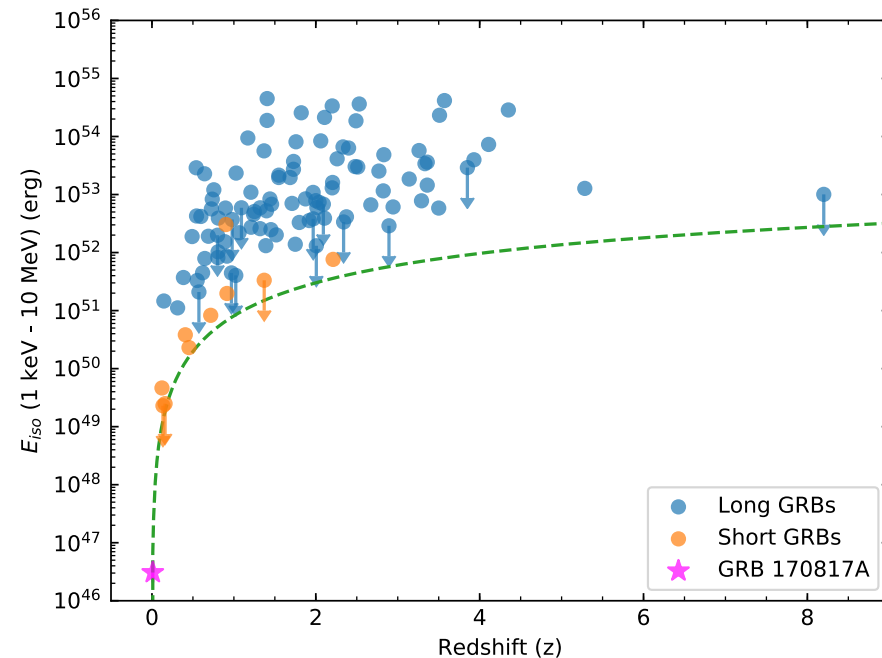
Astrophysical impact

- 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

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

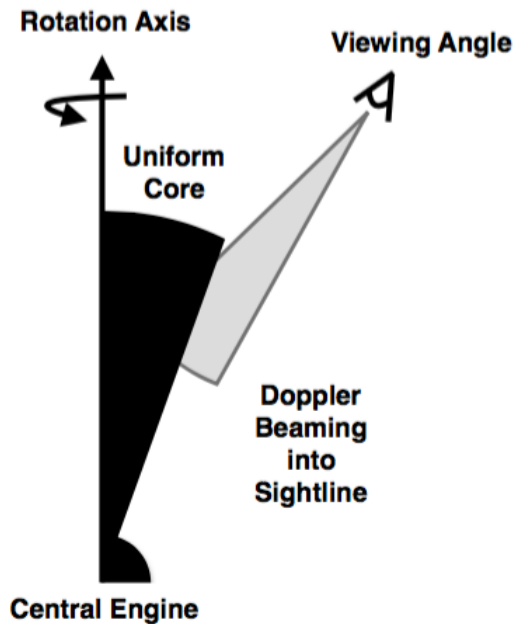
"Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A", ApJL in press (2017)



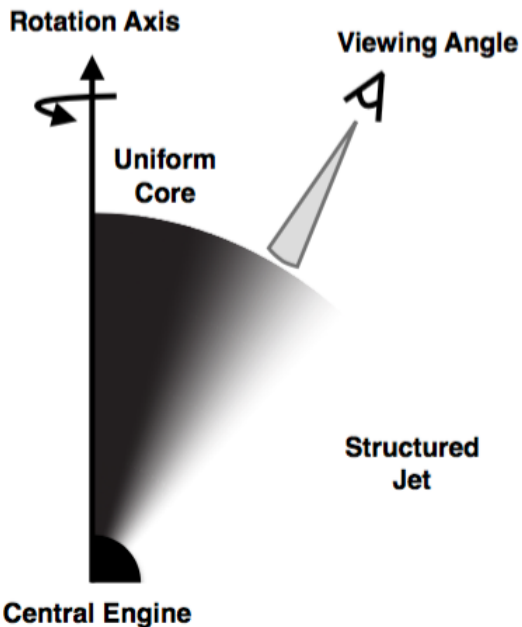
Possible scenarios

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

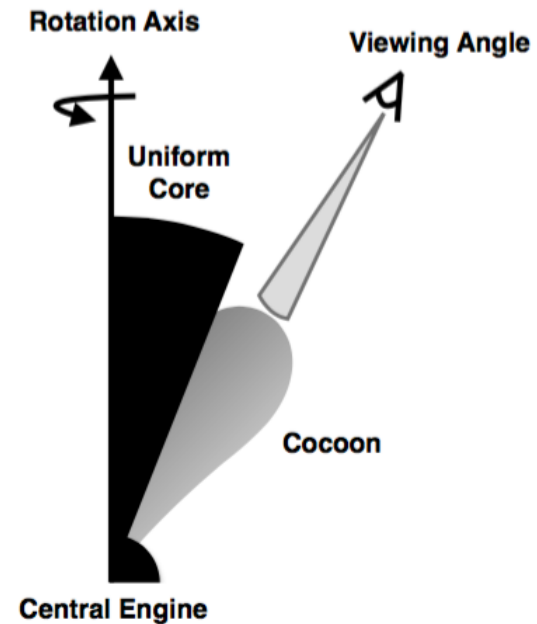
Scenario i: Uniform Top-hat Jet



Scenario ii: Structured Jet



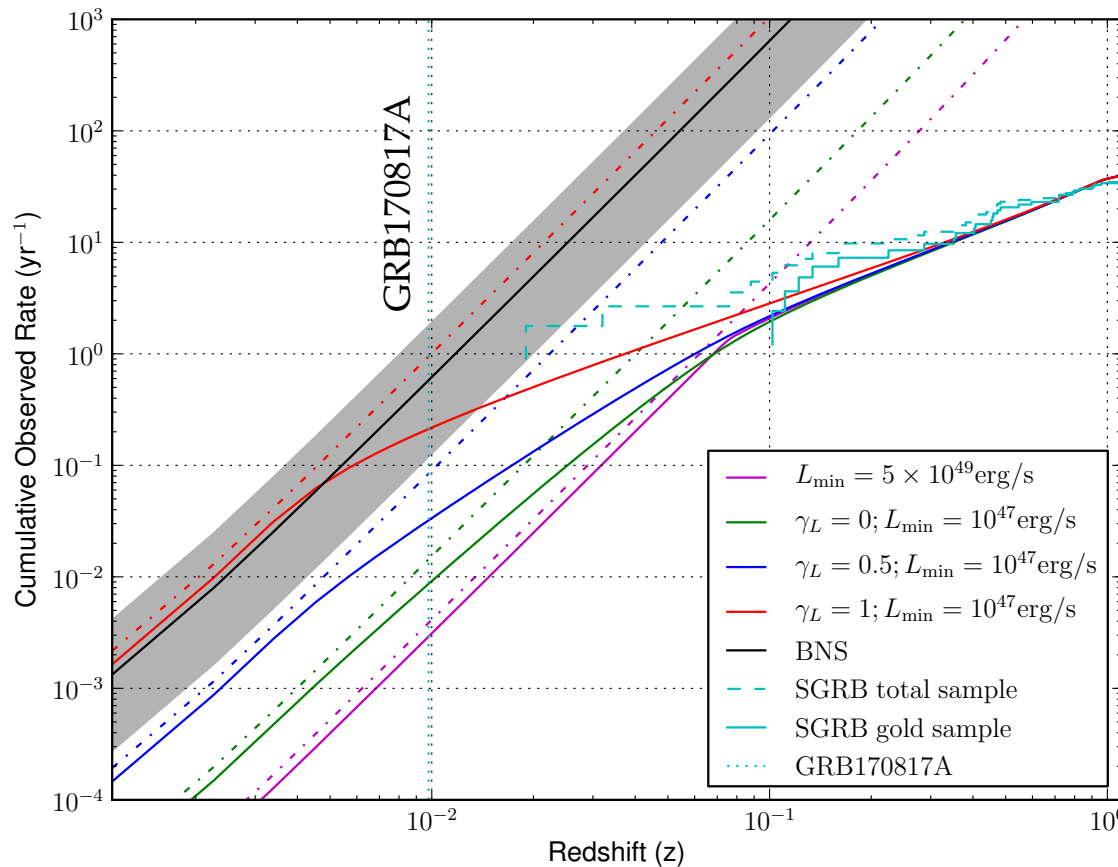
Scenario iii: Uniform Jet + Cocoon



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

Could we detect similar events ?

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



Known sGRB
population 40/year

BNS detections (/year):

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

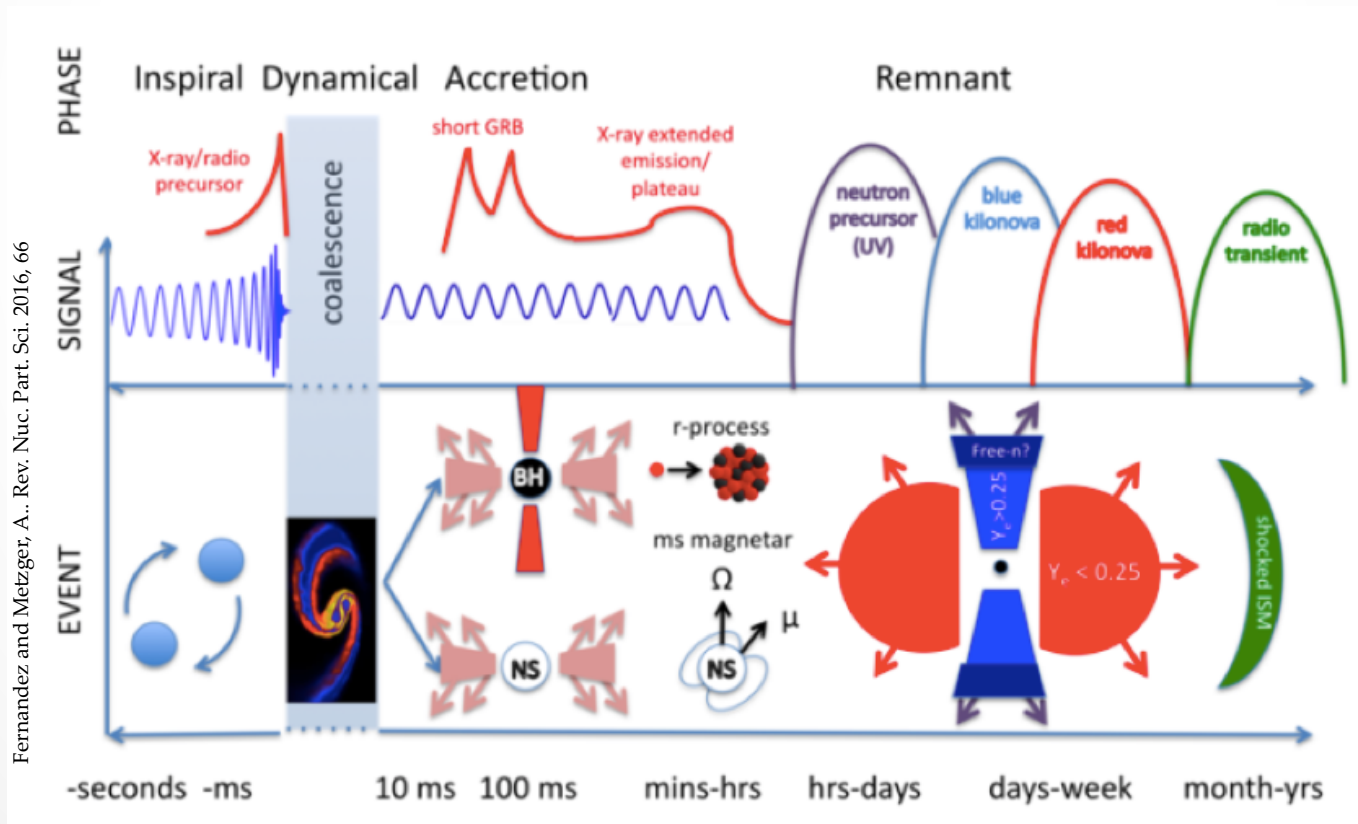
GRB detections (/year):

- O3 : 0.1-1.4
- Design : 0.3 – 1.7

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

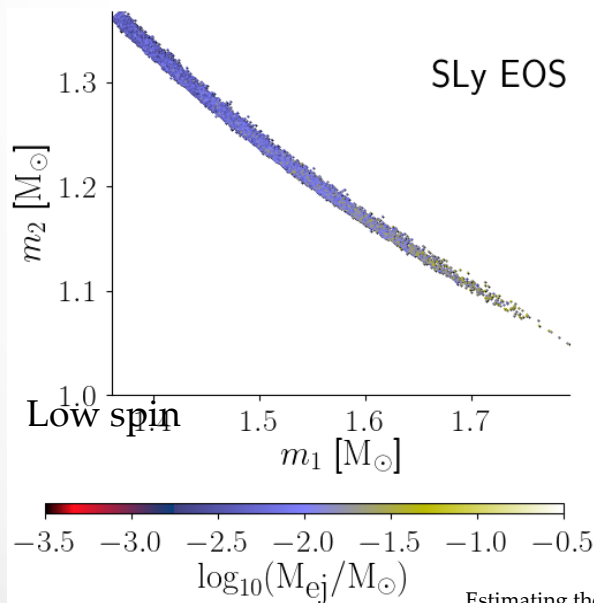
Kilonova

- 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

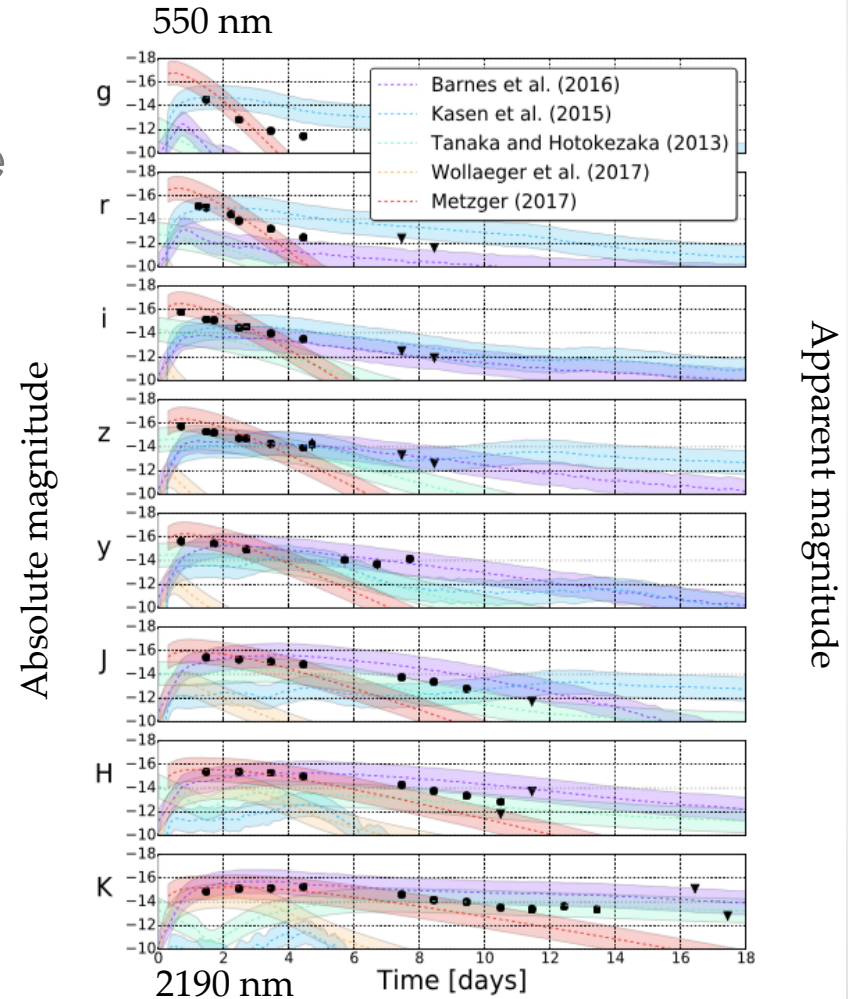


Kilonova prediction

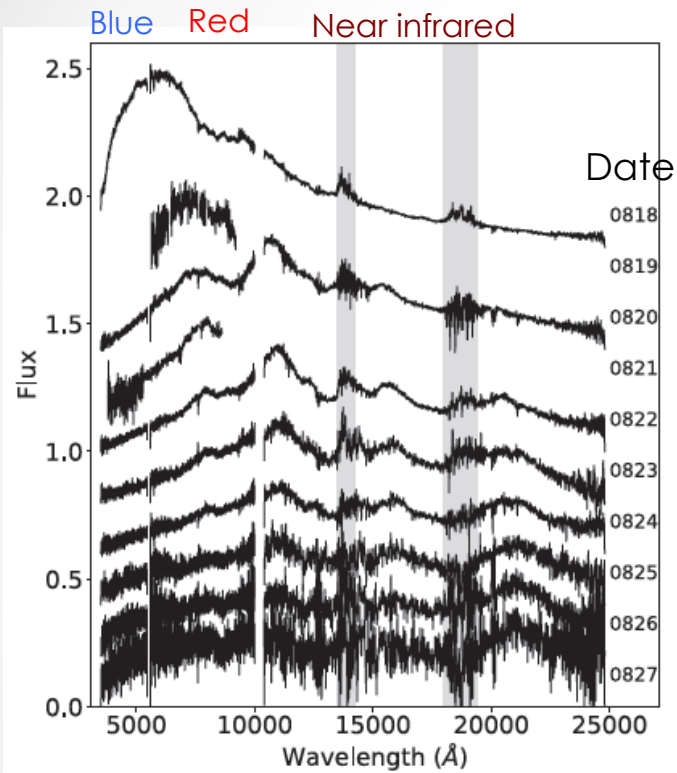
- GW masses inference + EOS -> predict ejecta mass
- $M_{\text{ej}} : 10^{-3} - 10^{-1} M_{\odot}$
- Predict light curves from visible to infra-red
- Could account for r-process material in our galaxy



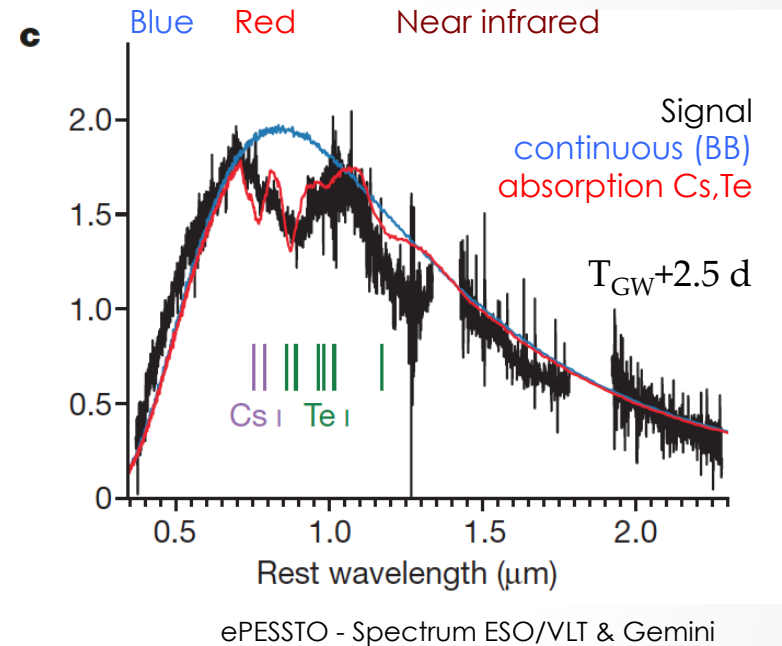
Estimating the contribution of dynamical ejecta in the kilonova associated with GW170717, Abbott et al,



Kilonova – spectral observations



Grawita Spectrum ESO/VLT & Gemini

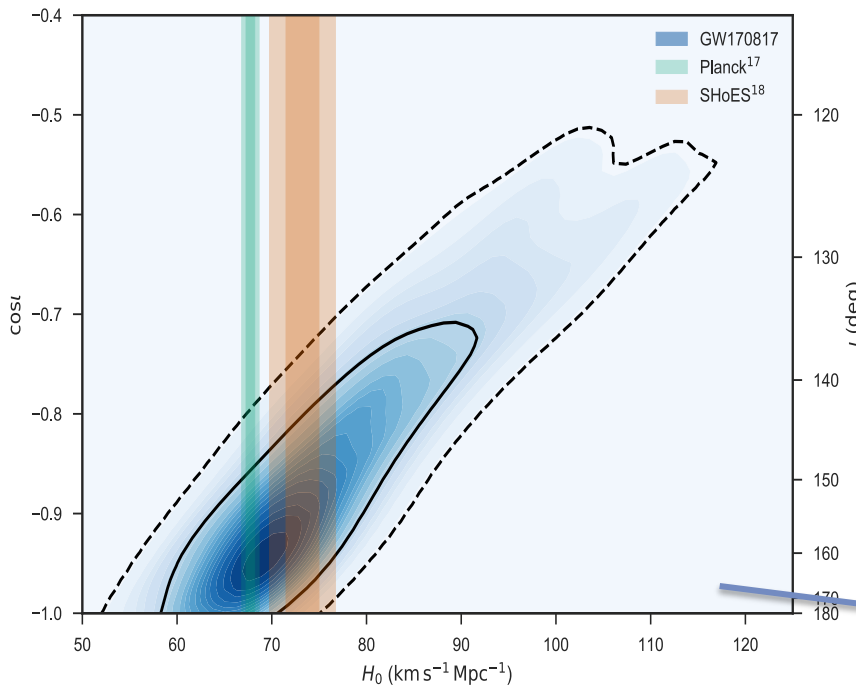


- Spectrum favor a relativistic ejecta
- Rule out supernova hypothesis
- 11000 K at day 1, 5000 K a day later, 1400 K 10 days later
- Spectrum show contributions from heavy elements

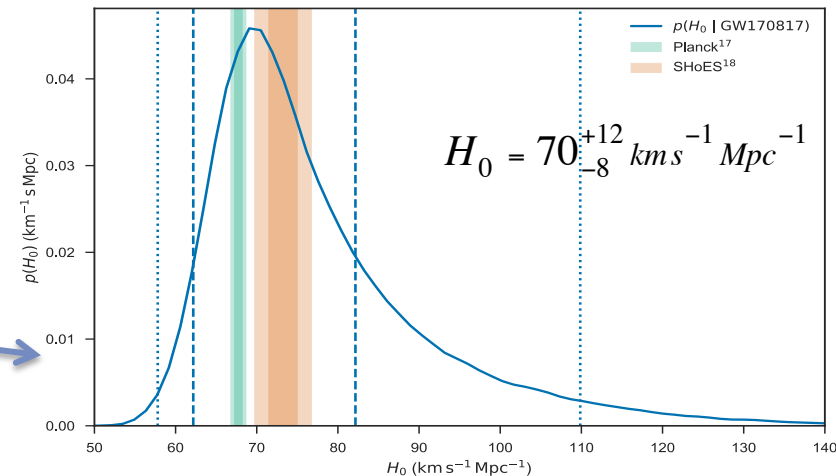
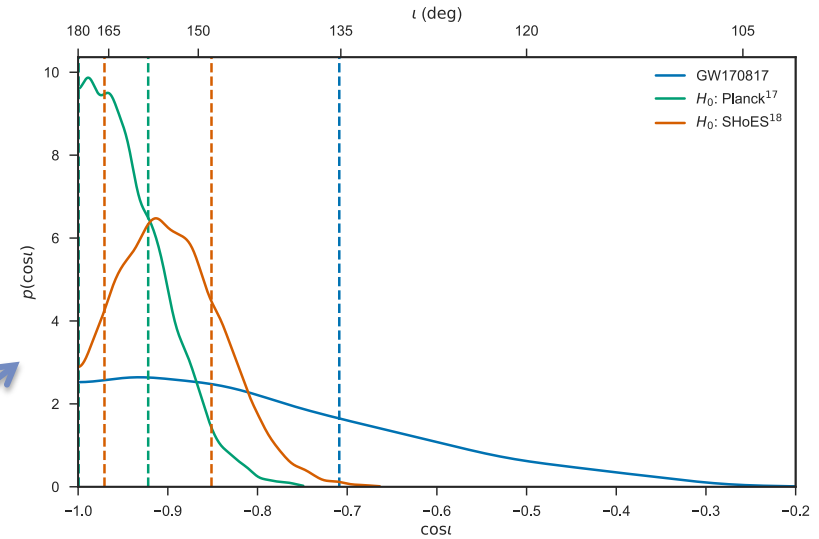
Hubble constant measurement

- For closed-by source : $v=H_0 D$
- Distance (GW) and orientation are correlated

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



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

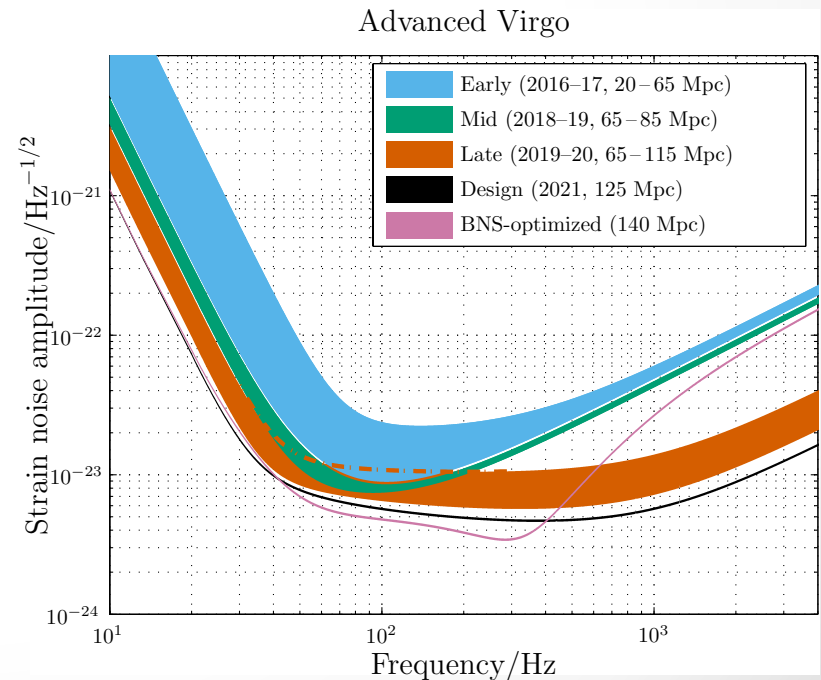
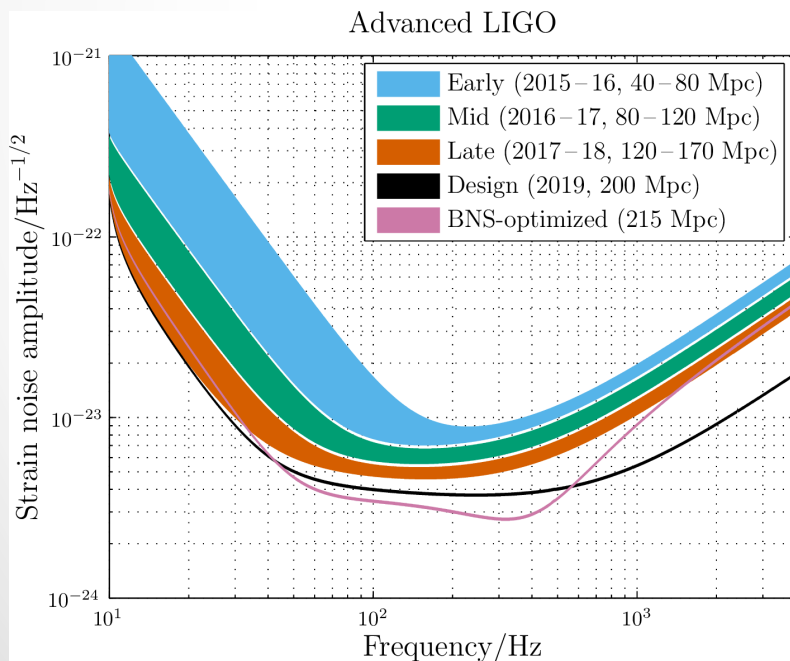


Main results with GW170817

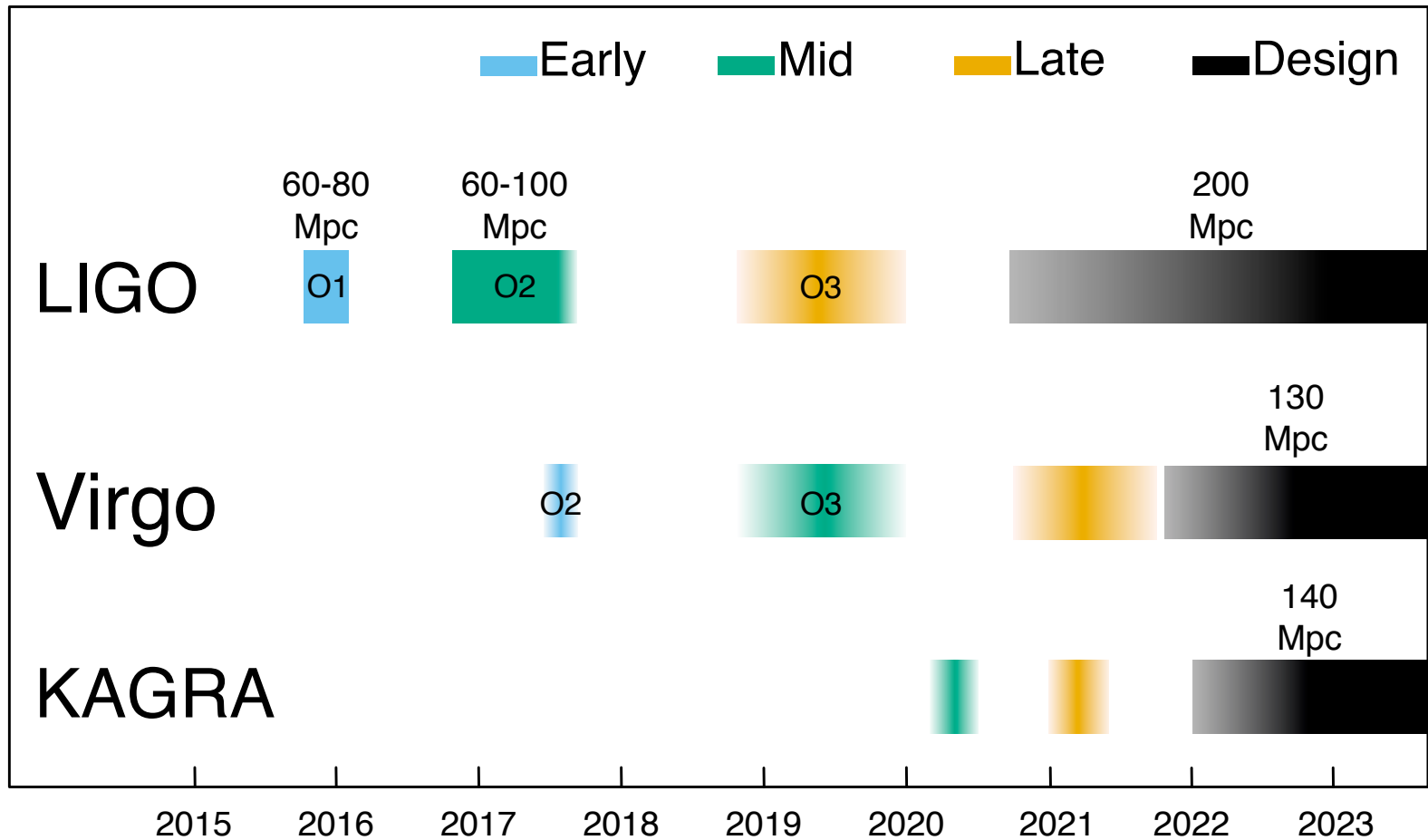
- GW170817 is the closest (and loudest) GW event ever observed
- First binary neutron stars system detected with GW
- Having three detectors allow to have a quite good localization and allow a full observation campaign
- Confirmed that this BNS is the central engine of a short GRBs – association with GRB170817A $> 5.3 \sigma$
- 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

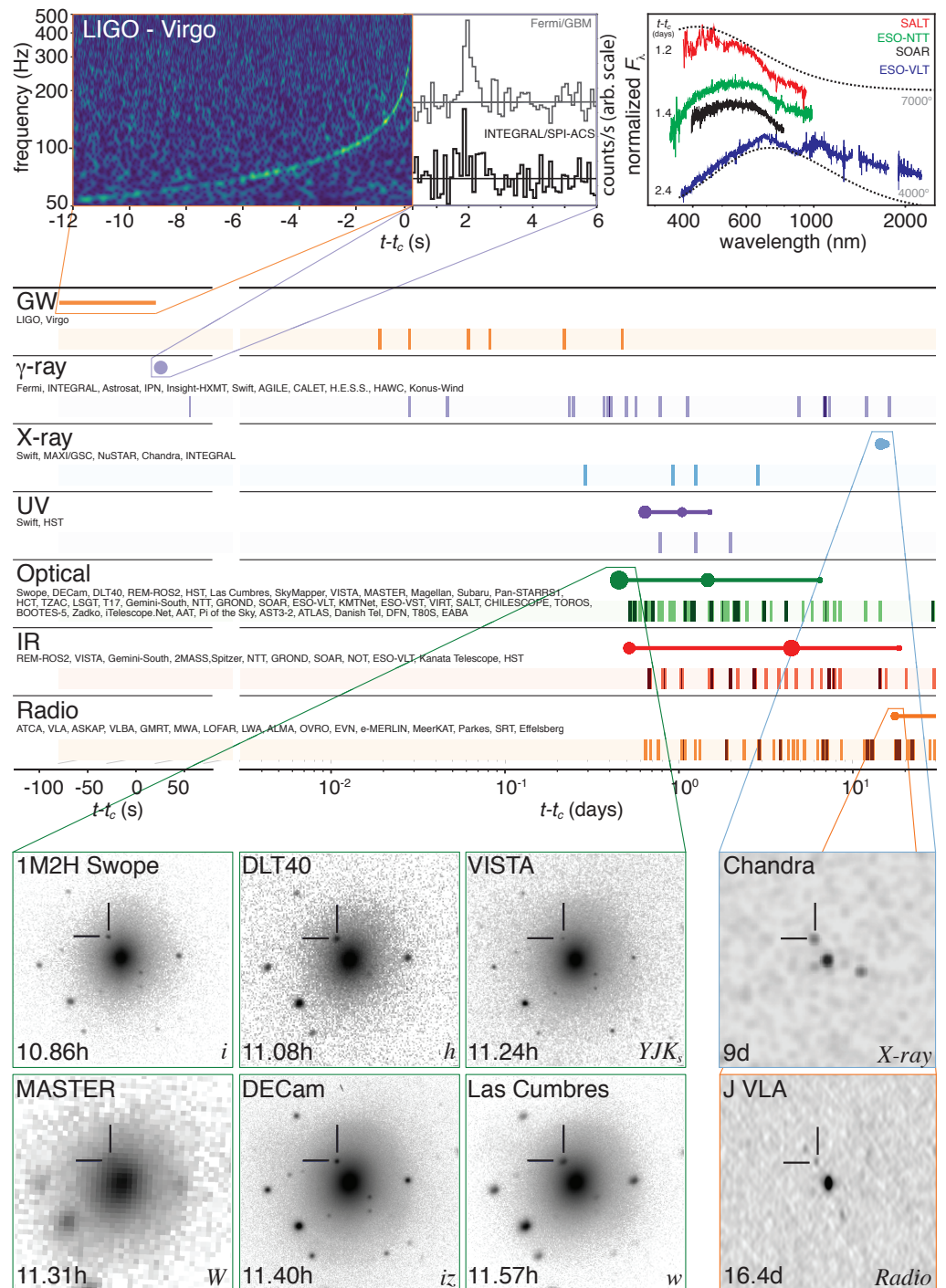


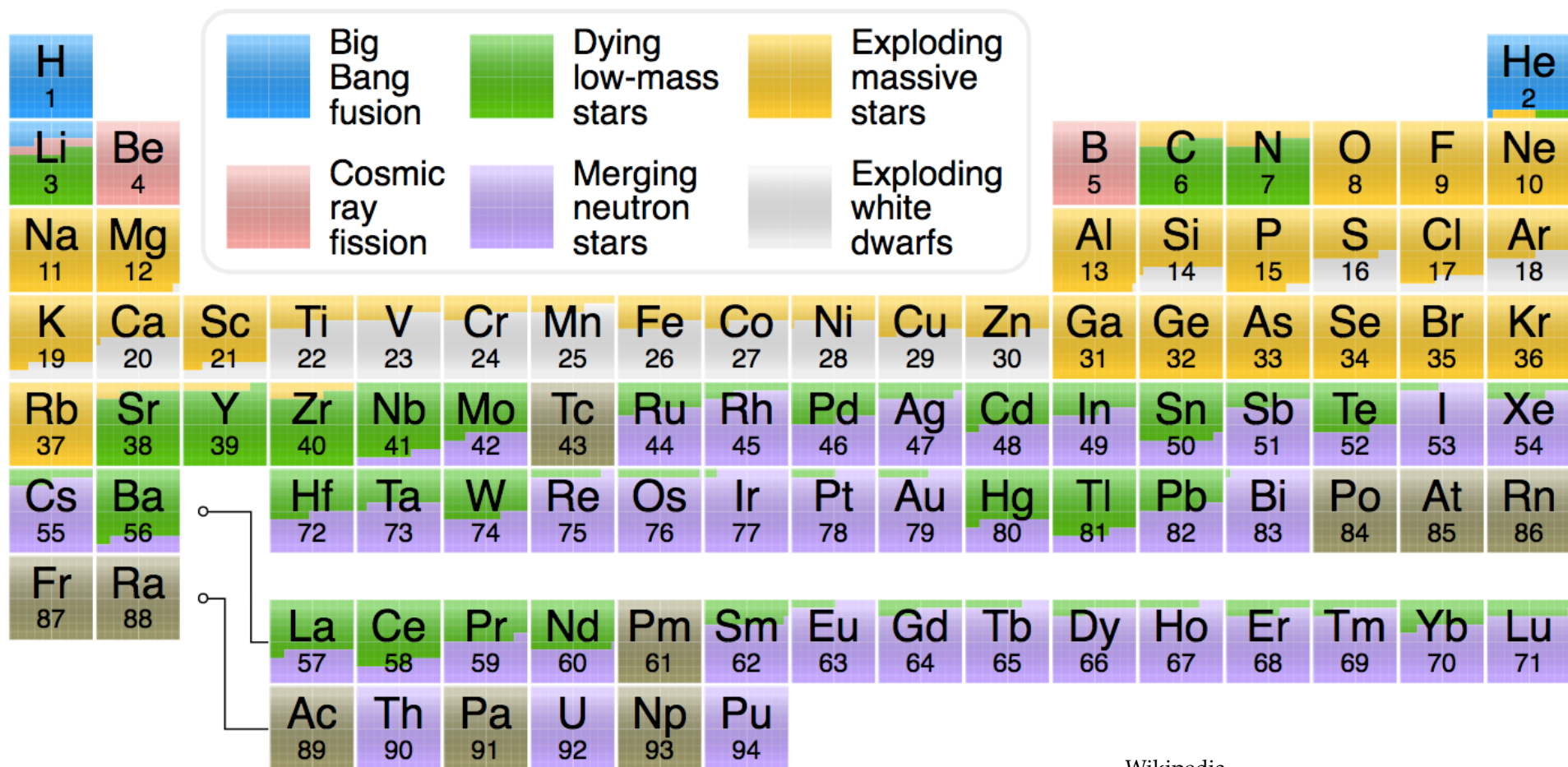
Futur is bright !

- 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 !

backup
...

The full campaign (up to now)





Wikipedia

