Observation of Gravitational Waves from a Binary Black Hole Merger In Advanced LIGO Hanford and Livingston detectors

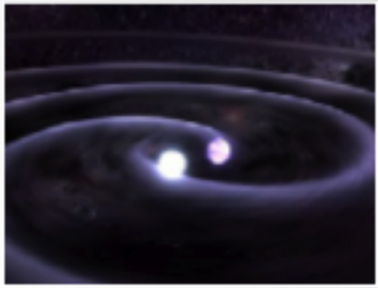
Nicolas Leroy, LAL CNRS/Université Paris-Sud

LIGO

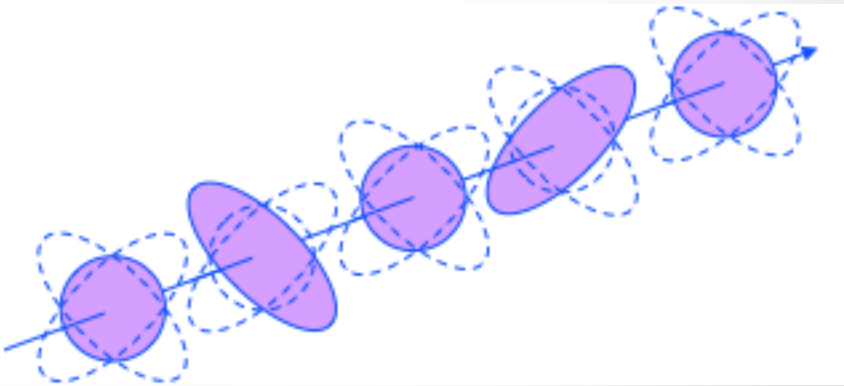
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

VIRGO

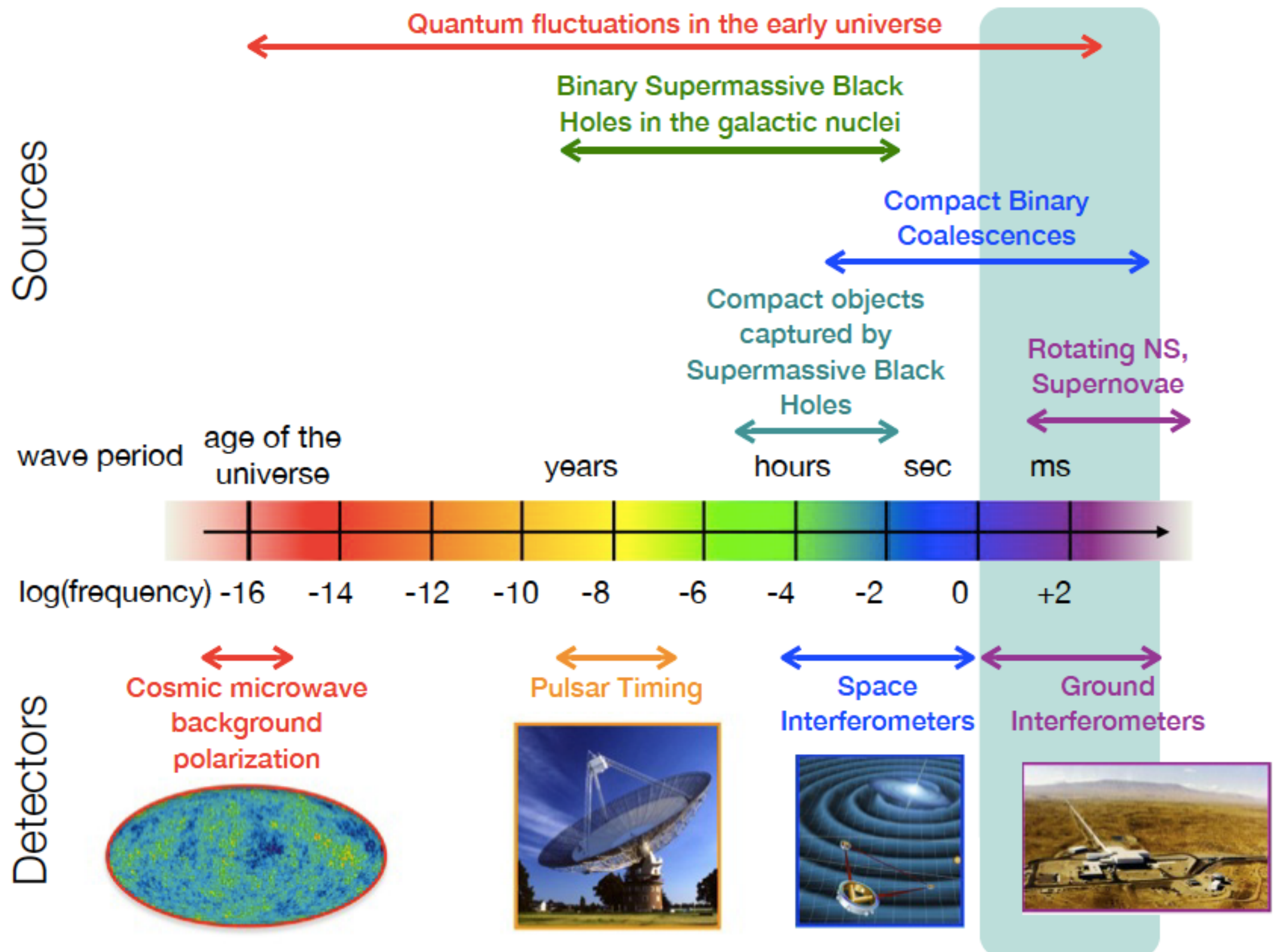
What are Gravitational waves ?



- Solution from General Relativity derived by A. Einstein in 1916
- Gravitation is a curvature of the space-time metric
- Any massive object will introduce a deformation of the metric
- Far from sources then 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

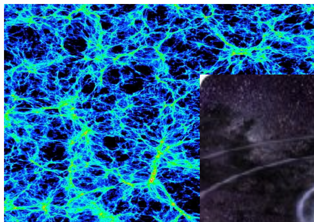


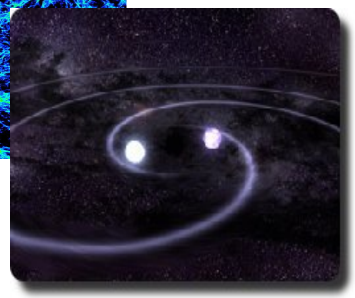
[Inspired from http://science.gsfc.nasa.gov/663/research/]

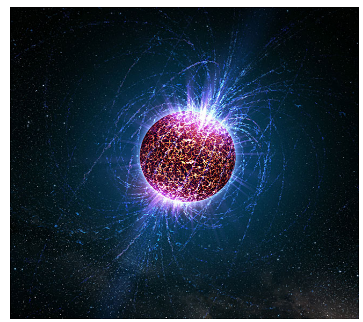
GW zoology

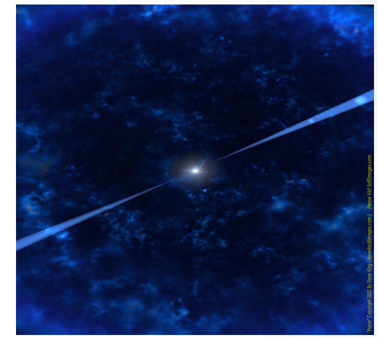
Short duration (1sec) — Long duration (∞)

Waveform known

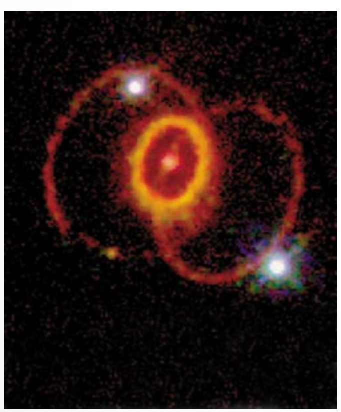




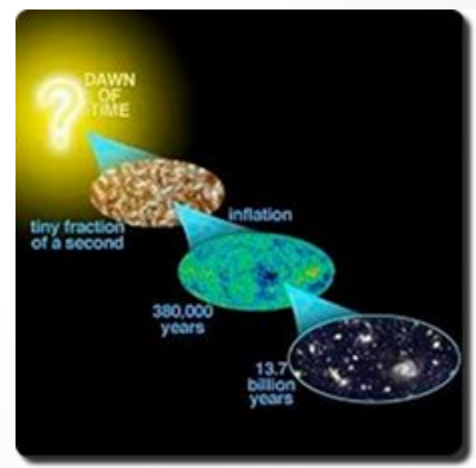




Waveform unknown



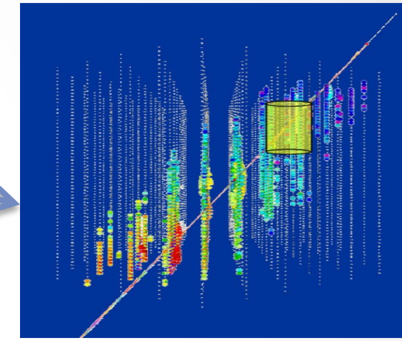
?



Multimessenger astronomy

Gamma-rays

HE (>1 TeV) ν

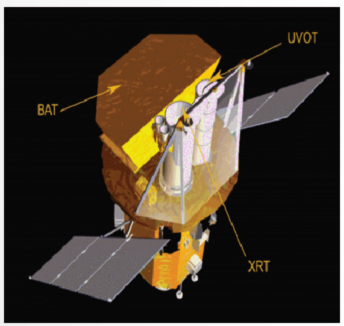


GRB

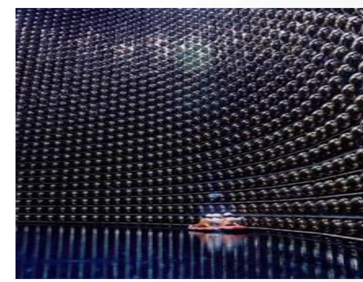
SGR/AXP

Supernovae
type II

X-rays



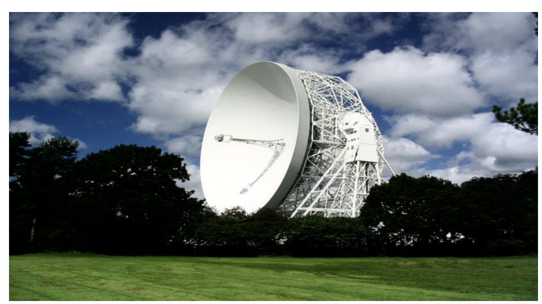
LE (MeV) ν



Giant Flare

Pulsar/
pulsar glitches

Optical



Radio

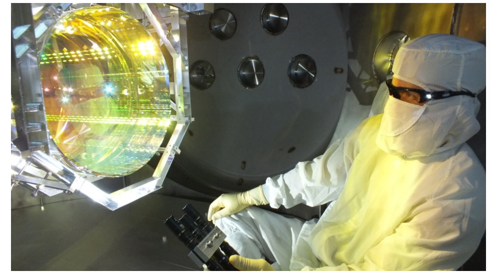
GW ground-based detectors science case

- First direct detection of a gravitational wave from coalescing binaries, core collapse supernovae, gamma-ray burst, pulsars, ...
- Test general relativity in strong field regime, measure GW speed
- Direct detection of black hole
- Probe progenitor for GRB
- Test equation of state of neutron stars
- Provide constraints on stellar population
- Cosmology : Hubble constant, primodial universe
- .....

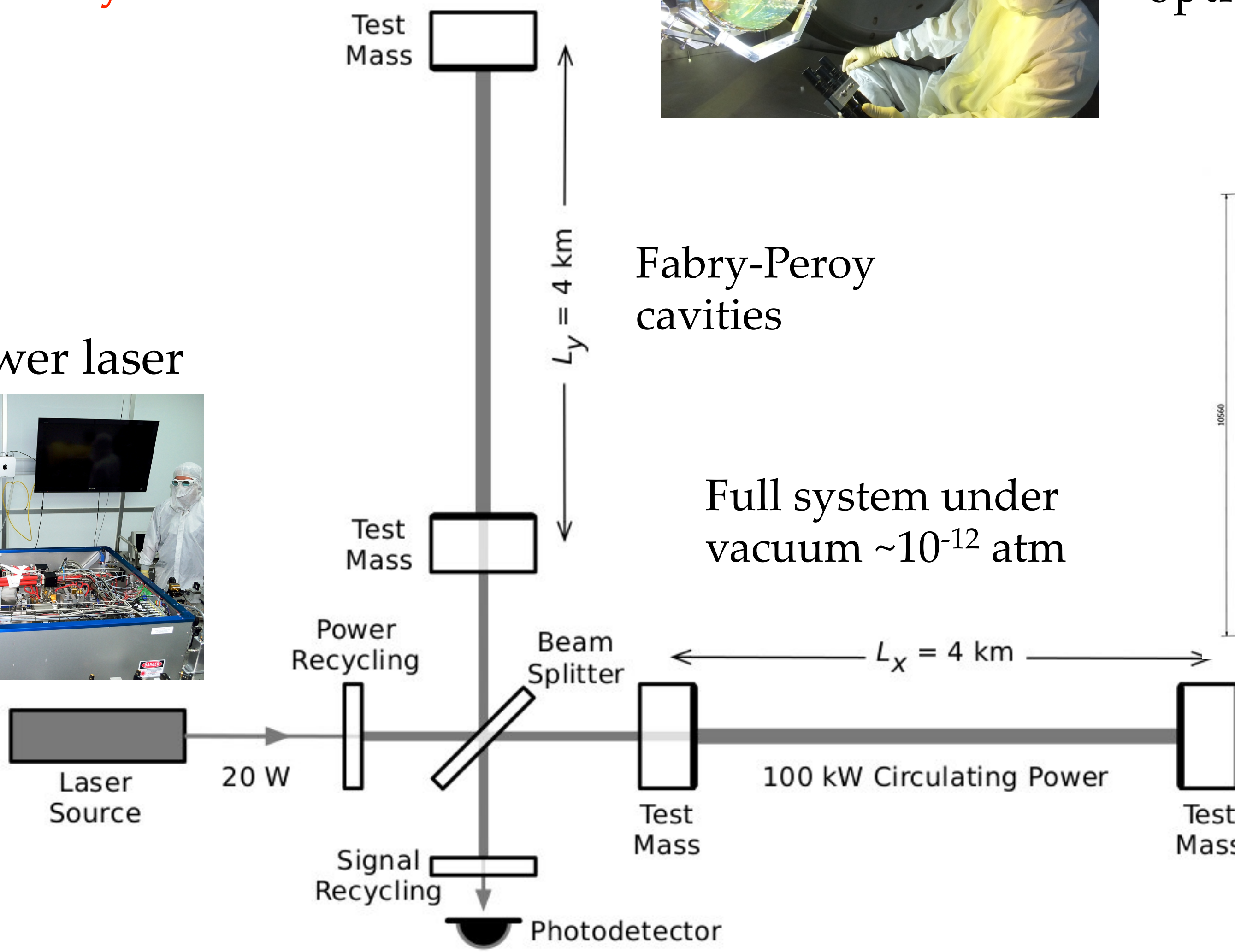
Detectors : using GW differential effect

Michelson interferometer

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

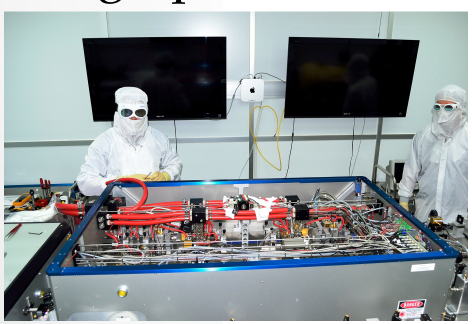


High quality optics

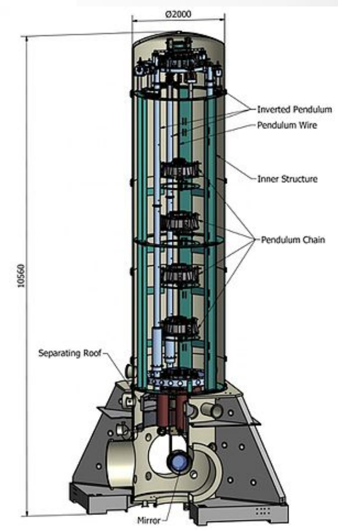


Fabry-Peroy cavities

High power laser

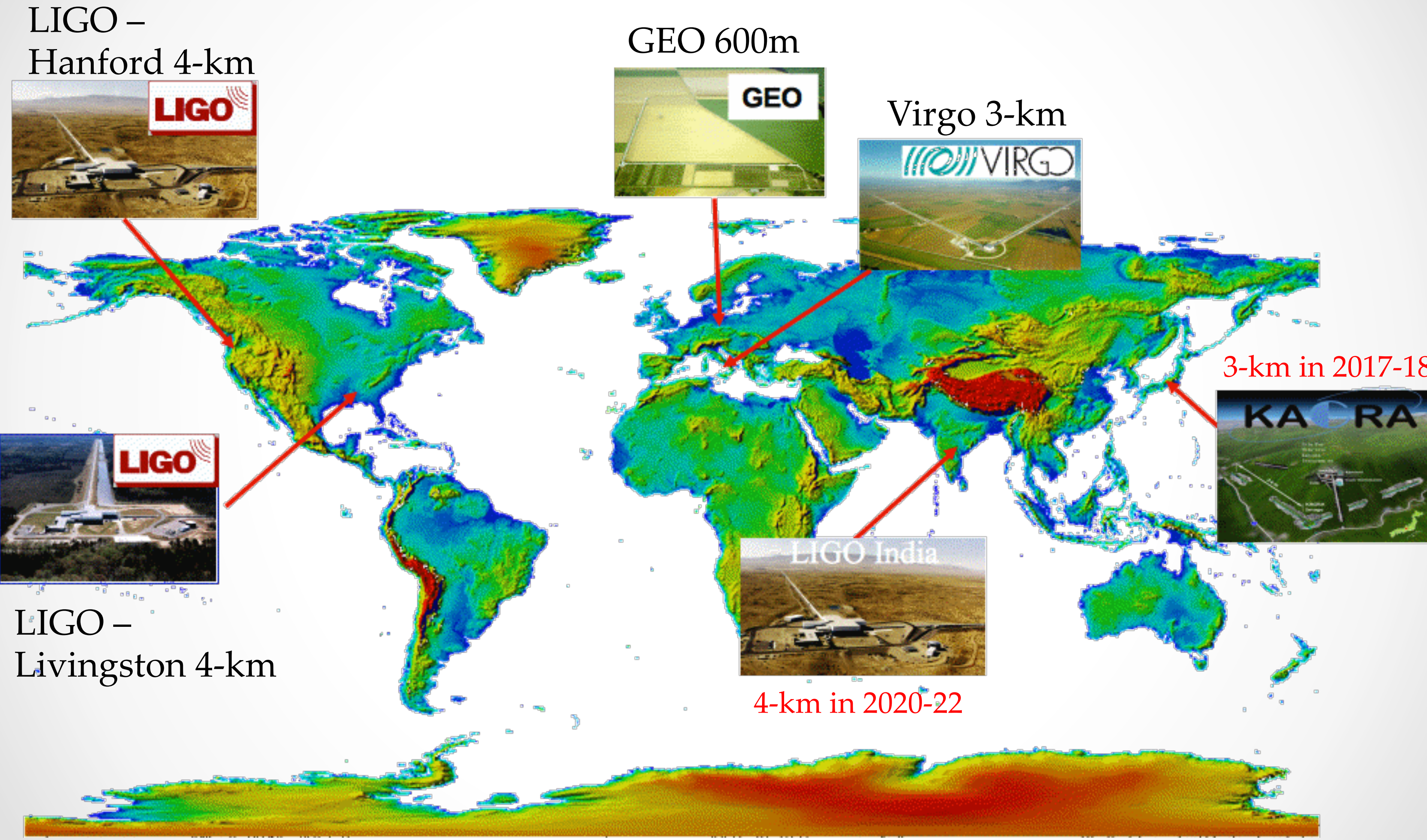


Full system under vacuum ~10^{-12} atm



Suspended optics

The GW detectors networks



Ground based network

- Increase the detection confidence
- Source sky localization
- Source parameters inference
- GW polarization determination
- Astrophysics of the sources

LSC
15 countries – 900 contributors

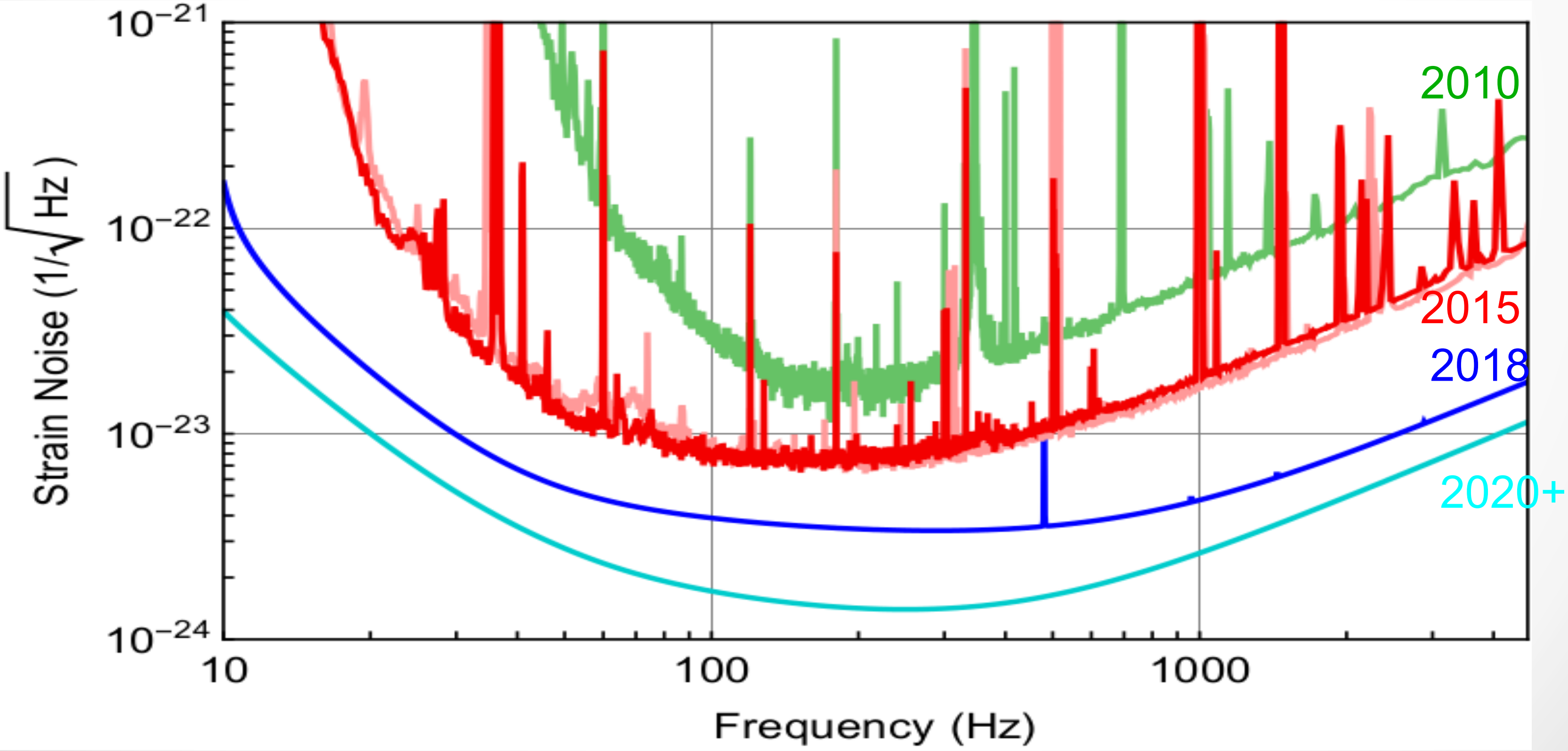
Virgo
5 countries – 200 contributors

Since 2007, LIGO, GEO & Virgo data are jointly analyzed by the LIGO Scientific Collaboration and the Virgo Collaboration.

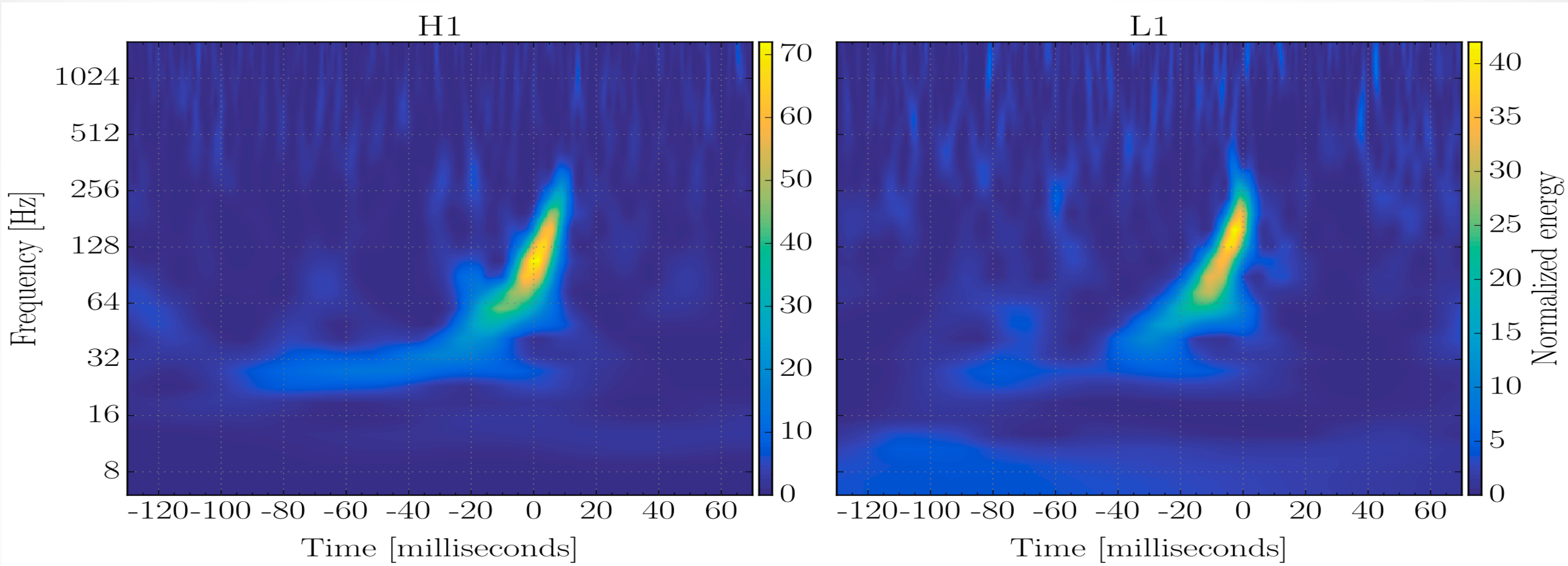
Start of Advanced LIGO run 01

- 2010-2014: installation
- 2014-2015: commissioning
- September 2015: O1 run start!

- Horizon (BNS): 70 – 80 Mpc
- 3-4 times more sensitive than LIGO
- 30-60 times larger in volume



The 14th of Septembre 2015



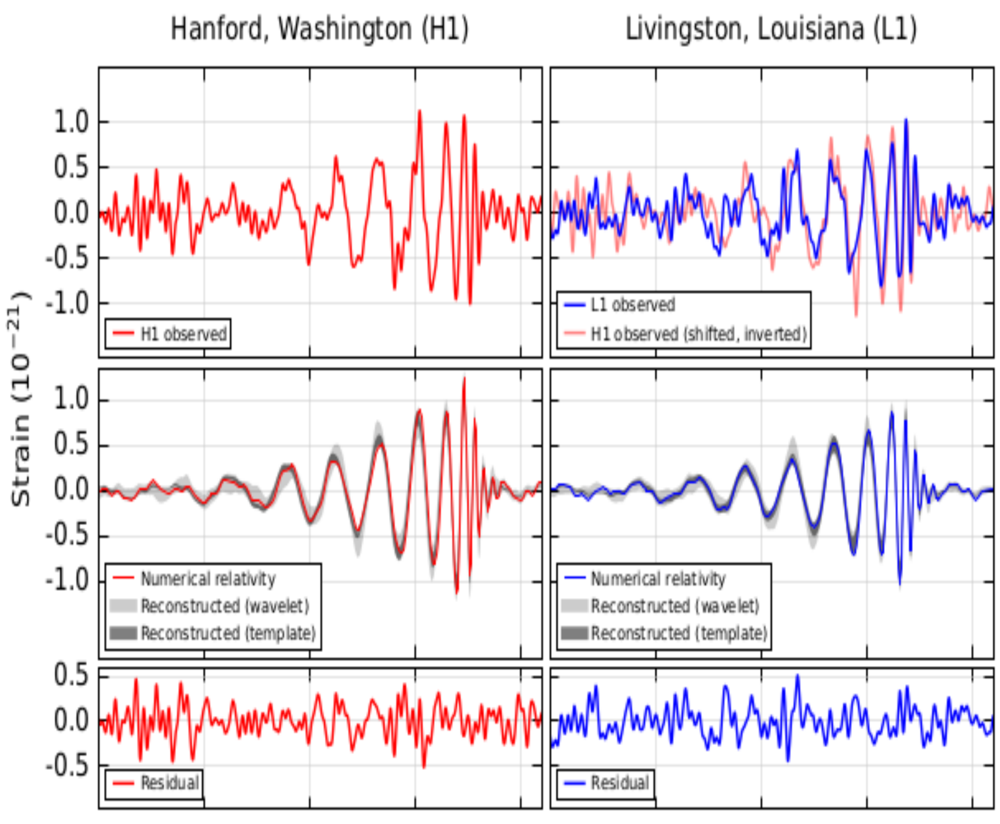
- Event reported within 3 minutes by an unmodelled search
- Within one hour, first (of a very long list) email reporting an interesting event
- In less than two hours nature and first parameters derived : BBH !!!
- Very low false alarm probability reported – message from directorate : this is not an hardware injection
- Decision to keep the interferometer in same state to accumulate enough data for background estimation

Time series of GW150914

Data bandpass filtered between 35 Hz and 350 Hz Time difference 6.9 ms with Livingston first

Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

Third Row –residuals



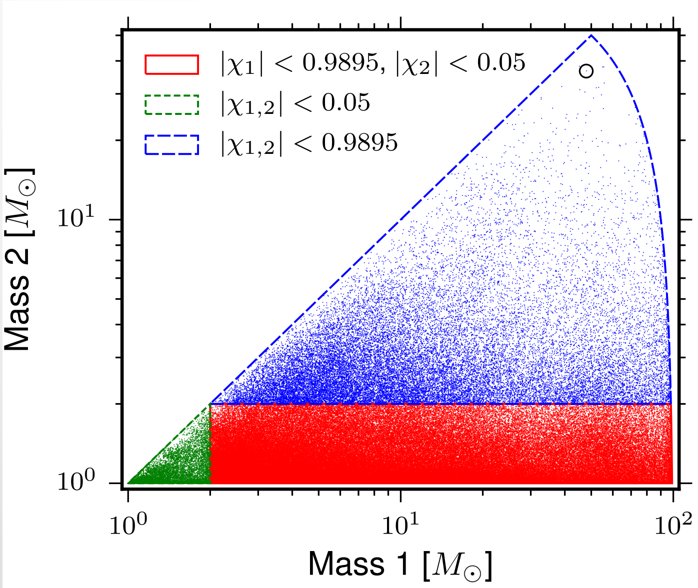
Search for modelled waveform

FFT of data

Template can be generated in frequency domain using stationary phase approximation

$$\mathcal{C}(t) = \int_{-\infty}^{\infty} \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

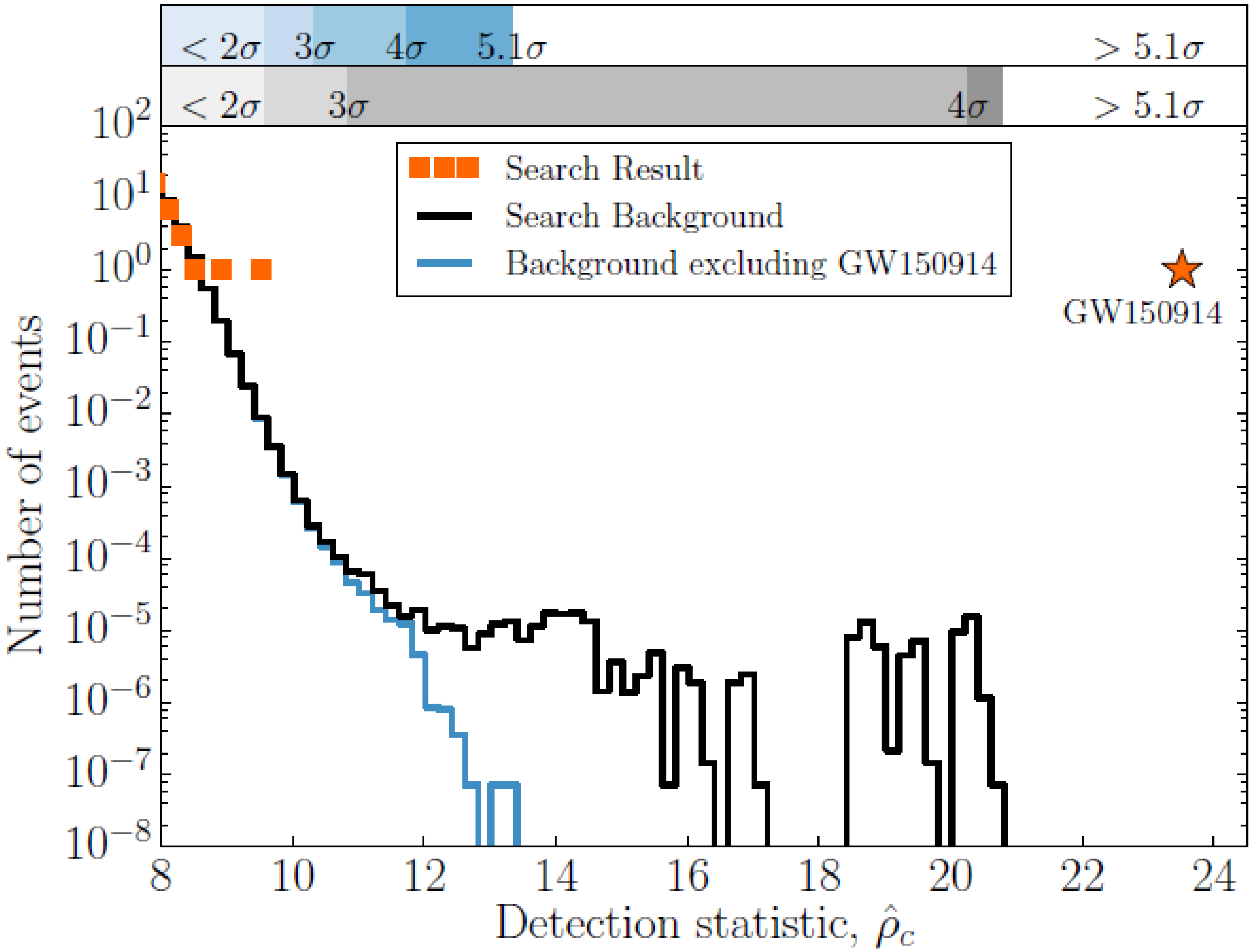
Noise power spectral density (in this case this is the two-sided Power spectrum)



September 2015 configuration:
Waveform templates: EOBNR with aligned spins
Online: low mass regime (<20 Msun)
Offline: 1-100 Msun – 250 000 templates

Chi2 test with best match template – coincidence 15 ms
Calculate quadratic sum of SNR in each detector
Background estimation done with time slides

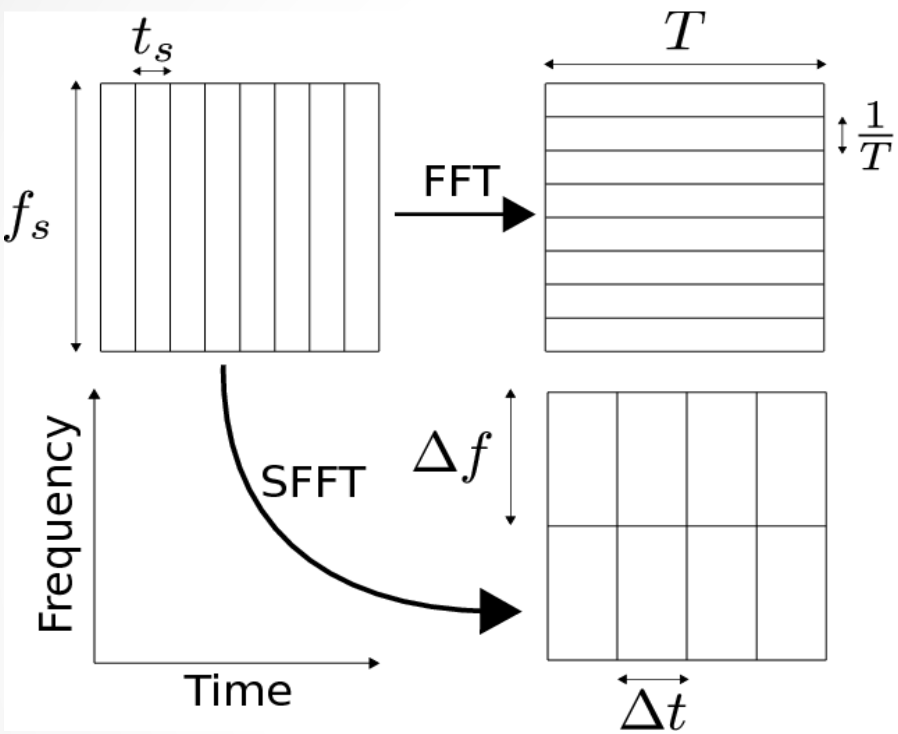
Results for the first 16 days coincident data

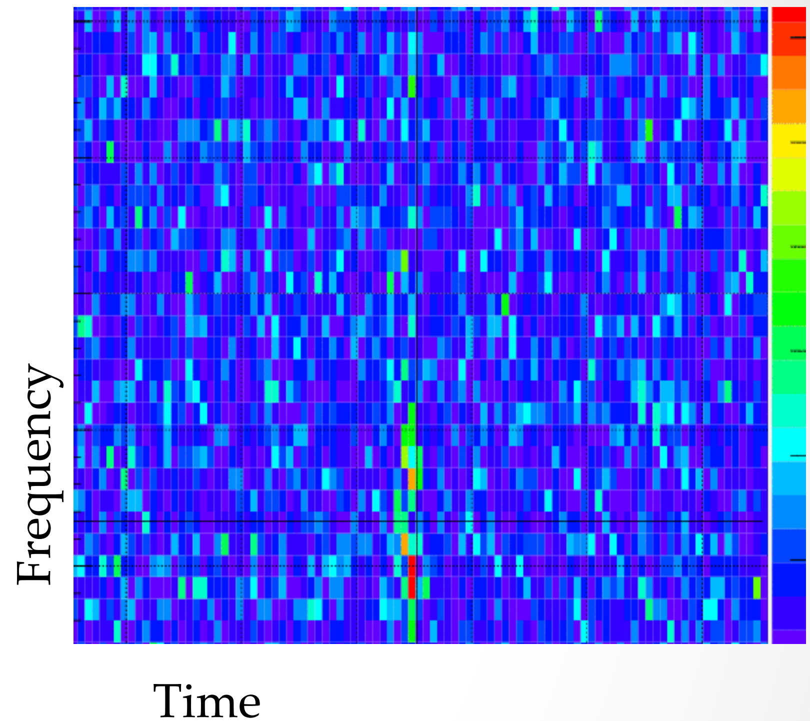


False Alarm Rate
< 1 / 200 000 years

False Alarm Prob.
< 2 10^{-7} - > 5.1 σ

Looking for unmodelled signal





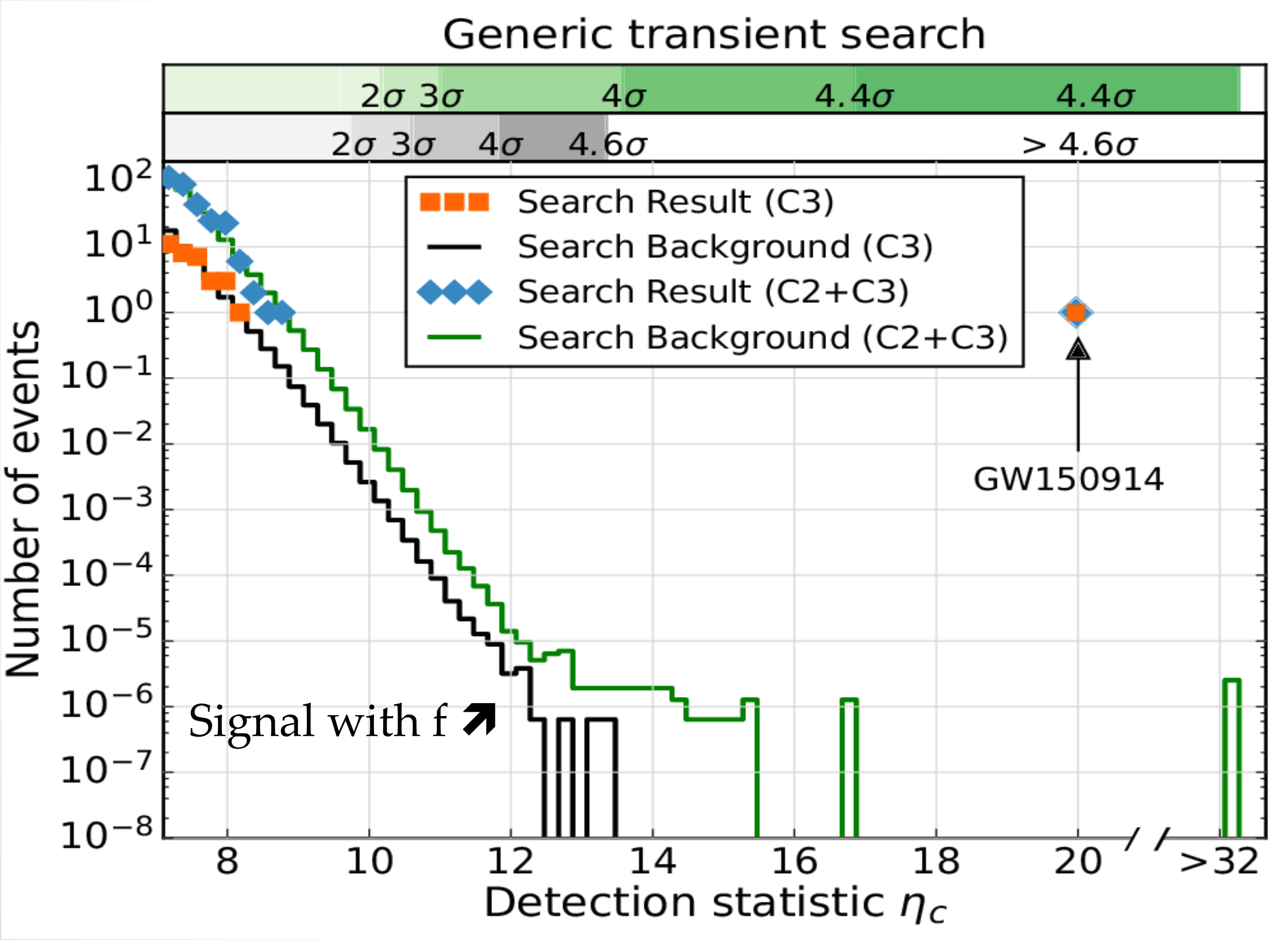
Excess in time-frequency map – using wavelet
Similar efficiency for high mass binaries (< 10 Msun)
Was running online
Background estimation with timeslides

Cross-correlation between detectors

$$\eta_c = \sqrt{\frac{2E_c}{(1 + E_n/E_c)}}$$

Residual noise energy

Results for the first 16 days coincident data



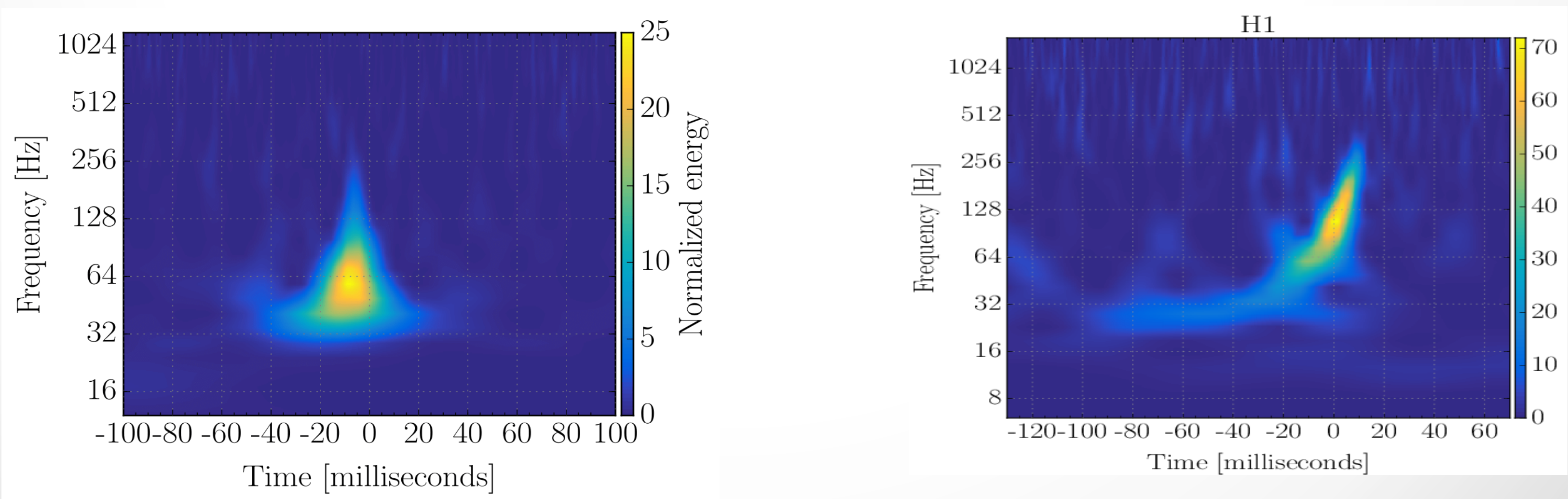
False Alarm Rate
< 1 / 67 400 years

False Alarm Prob.
< 2 10^{-6} - > 4.6 σ

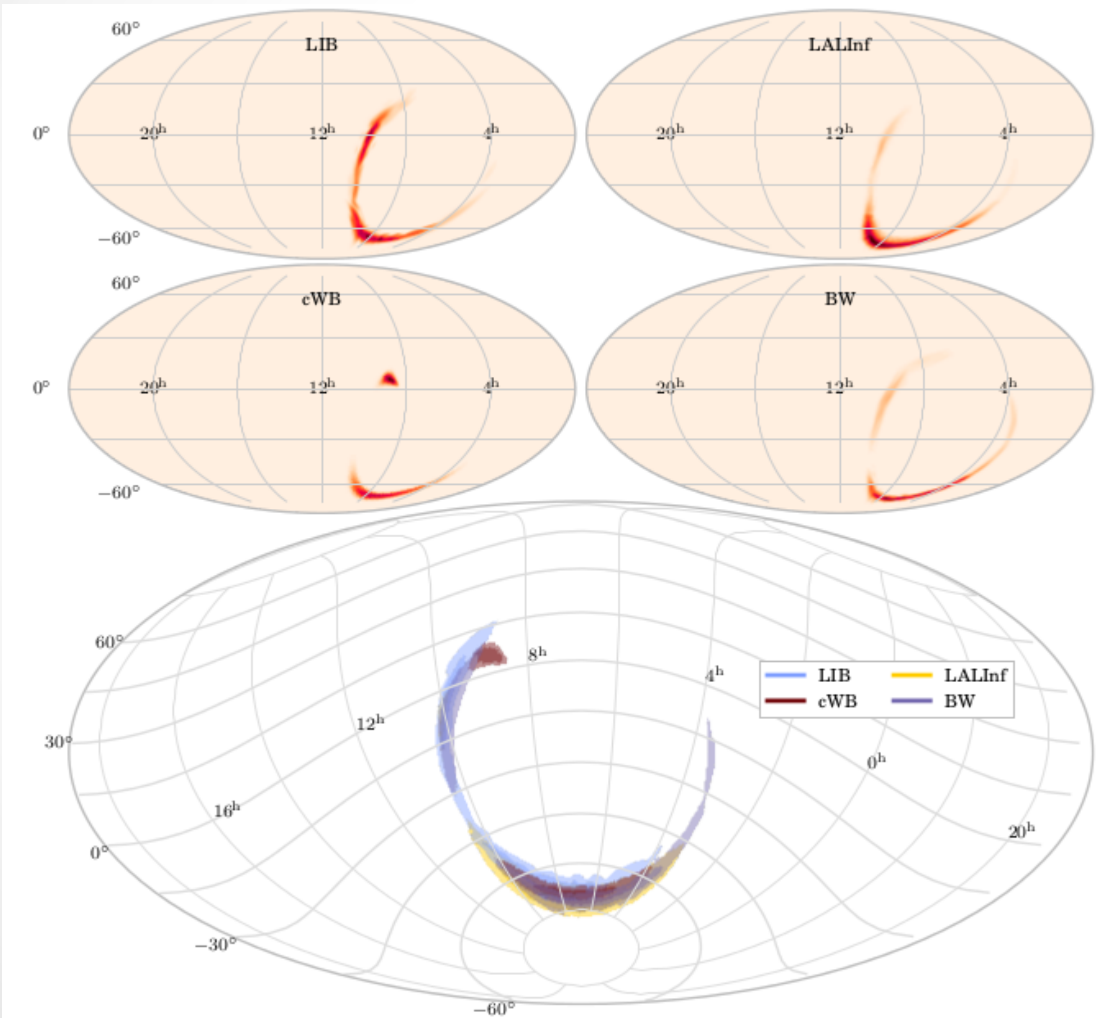
Around GW150914

- Noise investigation: 200,000 auxiliary channels scrutinized
  - Un-correlated noise: anthropogenic, earthquakes, radio-frequency modulation, unknown origin / known family glitches.
  - Correlated noise: potential EM noise sources (lightning exciting Schumann resonances, solar wind, …).
- Detector's control systems have been checked for hacking hazard (thorough investigation to rule out that none has injected a signal).
- Detectors outputs are stable for one month after the event

One of the loudest background trigger compared with the event

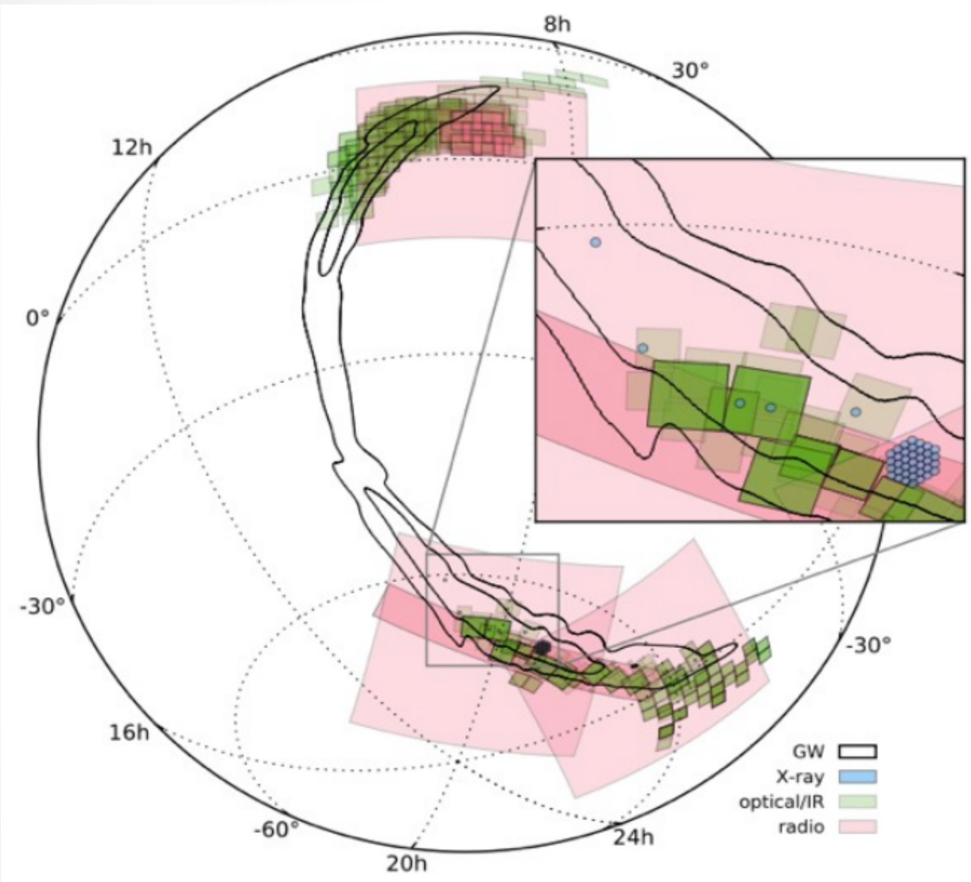


Sky location



Almost 600 sq
different pipelines with
different assumptions got
similar results

Follow-up with externals observatories



Alert sent to a private network with 48 hours of delay
Followed up by 21 teams

cWB sky map

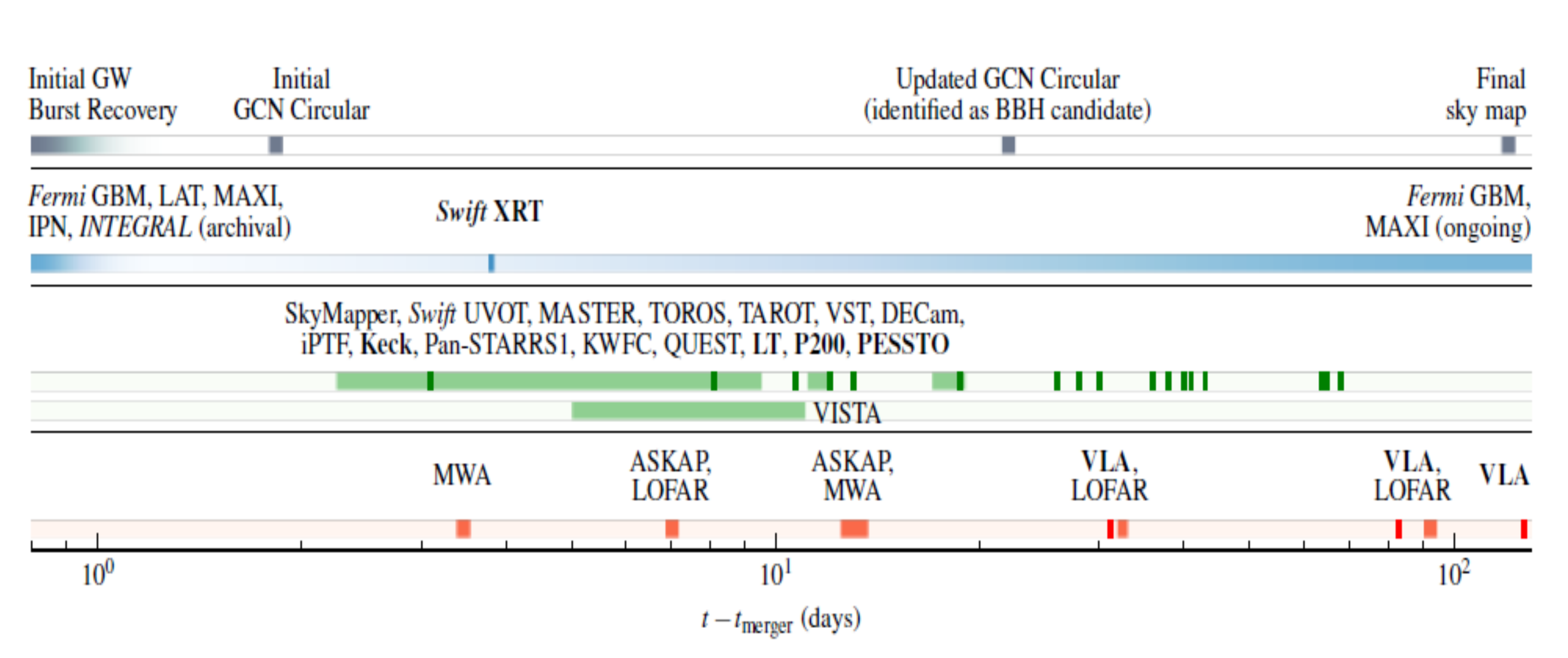
γ / X-ray observations

Optical observations

Radio Observations

External observatories first focus on BNS systems

Follow-up with externals observatories

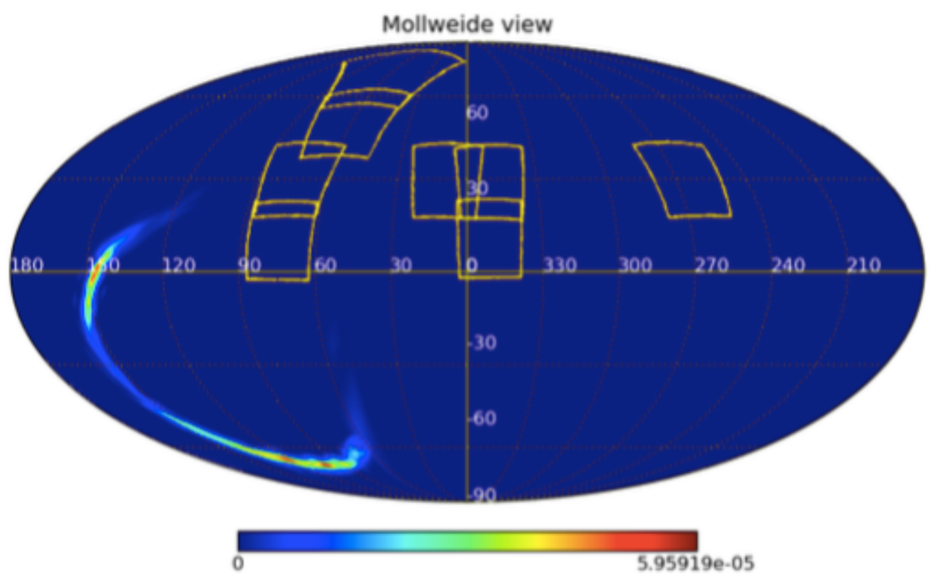


No clear signal yet reported

Follow-up with SVOM

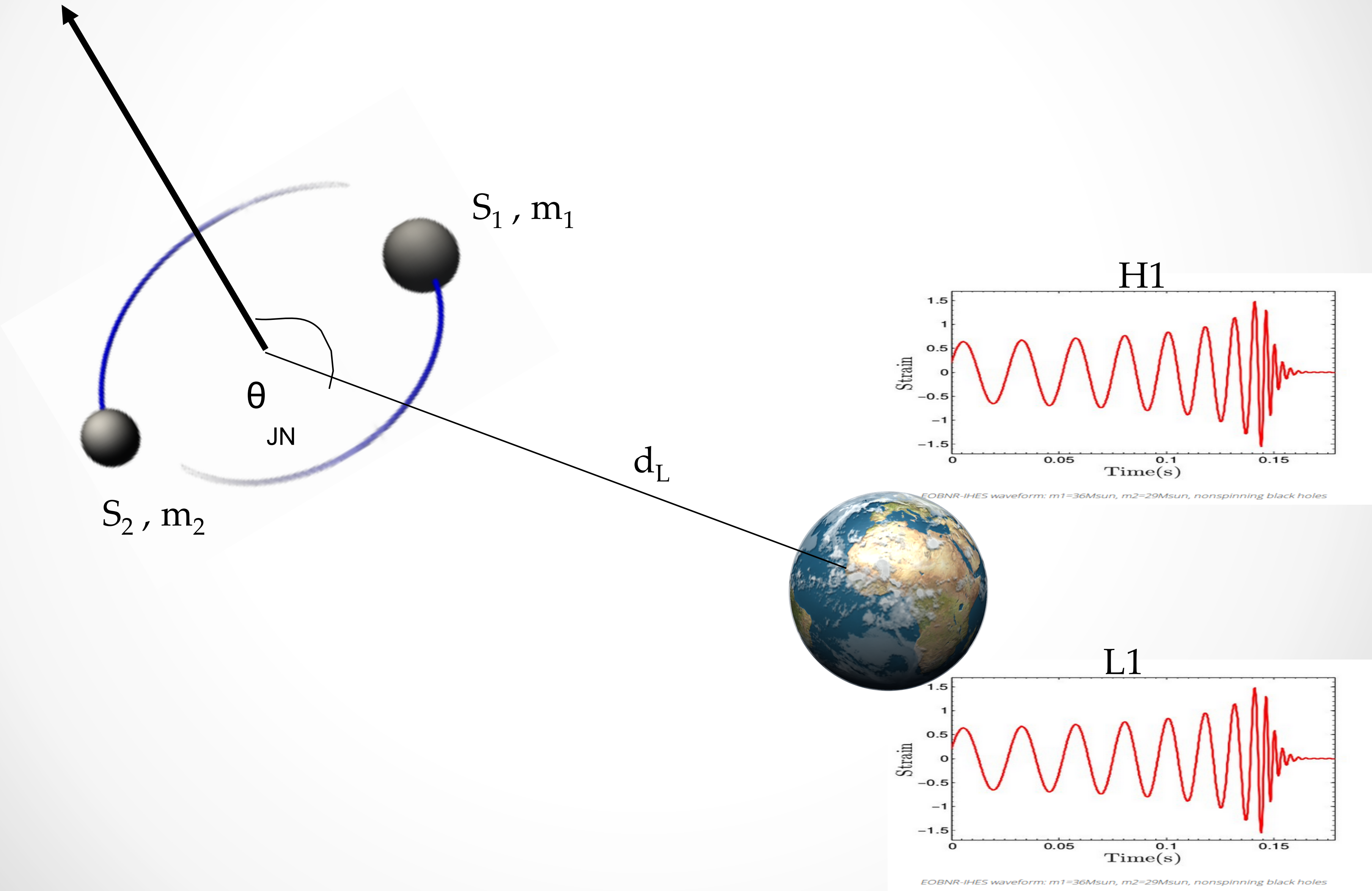
Jianyan Wei and Chao Wu

- At the time of the alert there was bad weather without the possibility to peform follow-up with mini-GWAC
- Search done on archival data at the time of the event shows some observation time – but we were a bit unlucky

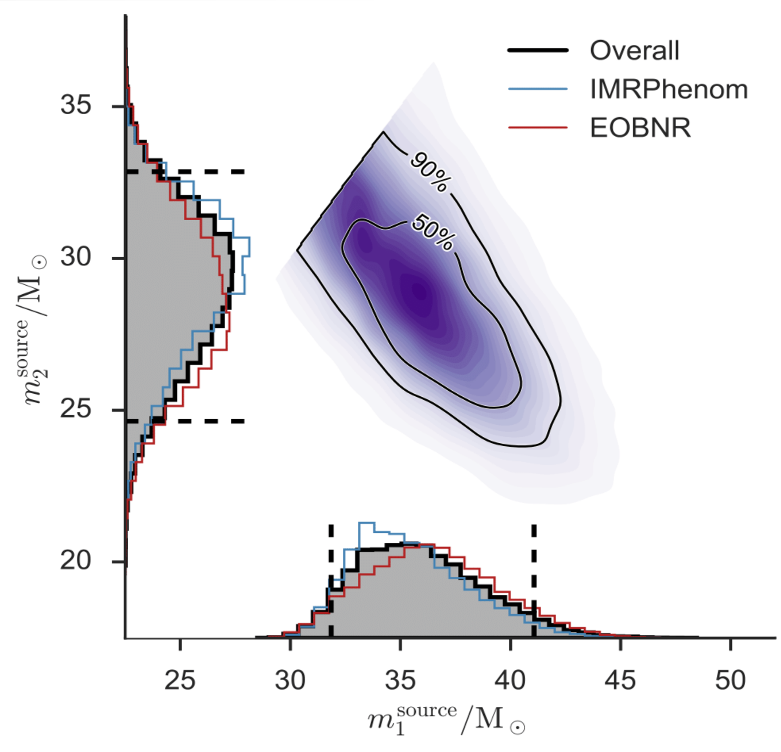


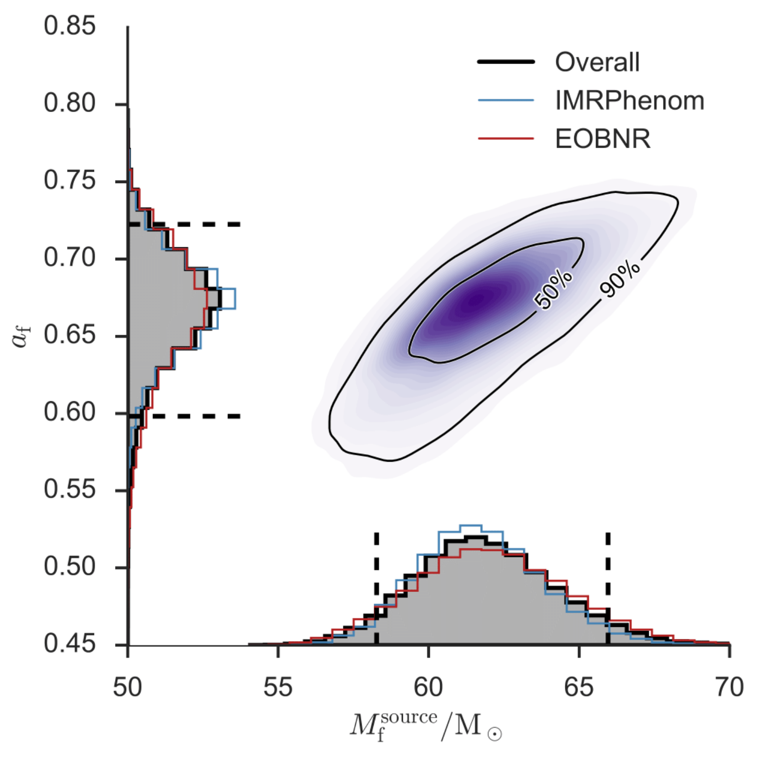
Event 20150914

Parameters of the source



Parameters inference

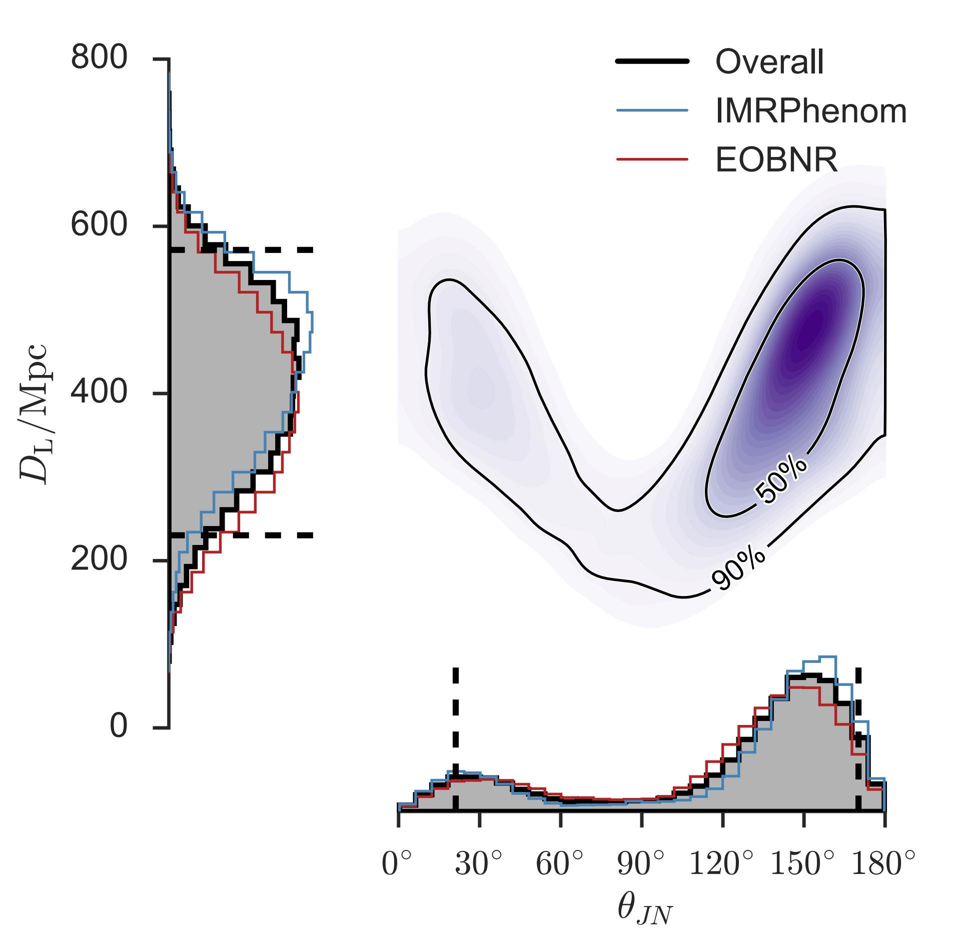




Initial masses

Final mass and spin

Parameters inference



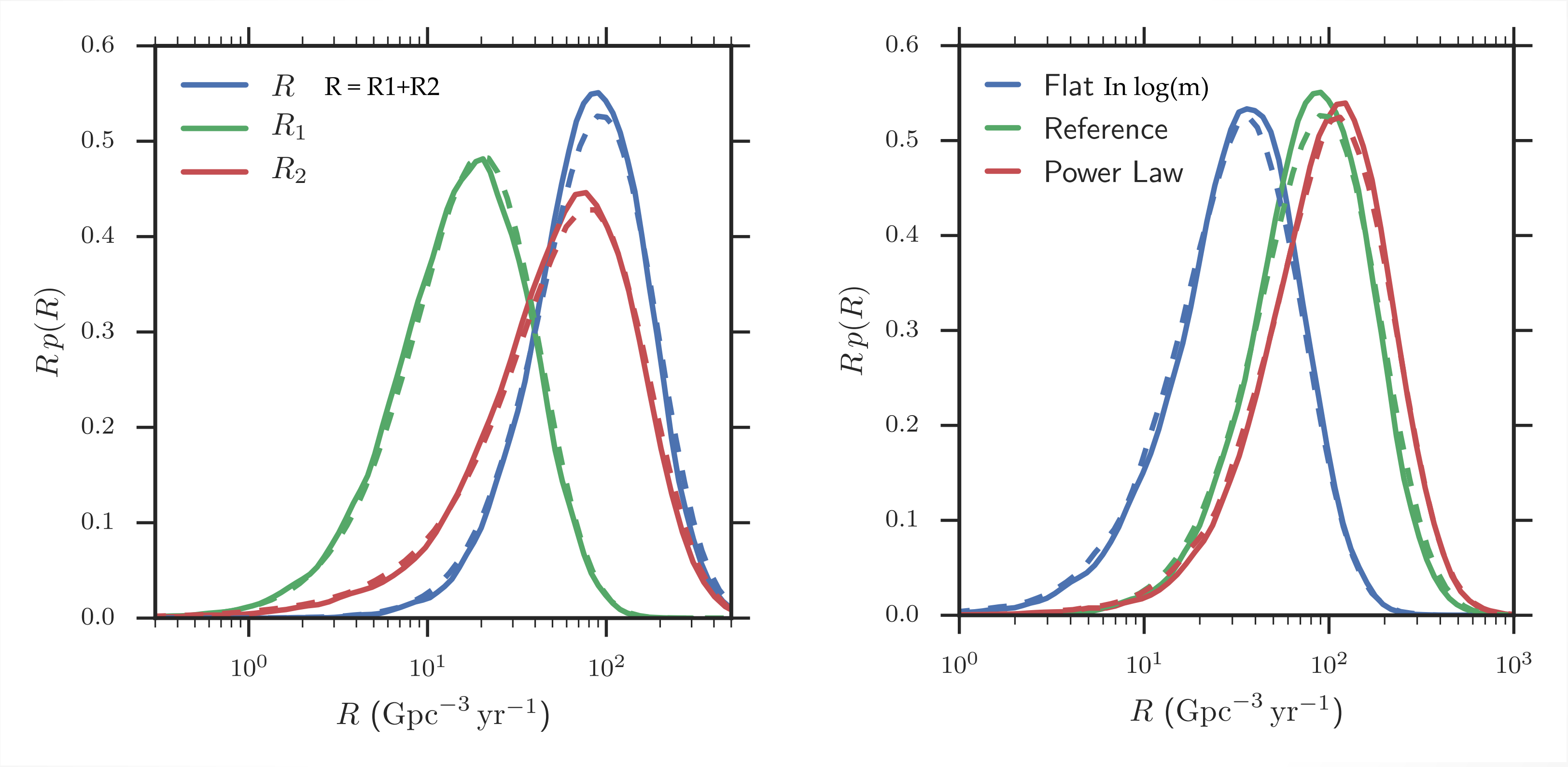
Distance vs inclination angle

Main parameters

Primary black hole mass	$36^{+5}_{-4}\ M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ M_\odot$
Final black hole mass	$62^{+4}_{-4}\ M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

- We observe a coalescence of 2 black holes with similar mass
- 3 $M_\odot$ in energy were radiated through GW emission – highest luminosity ever observed
- Final object is a Kerr black hole

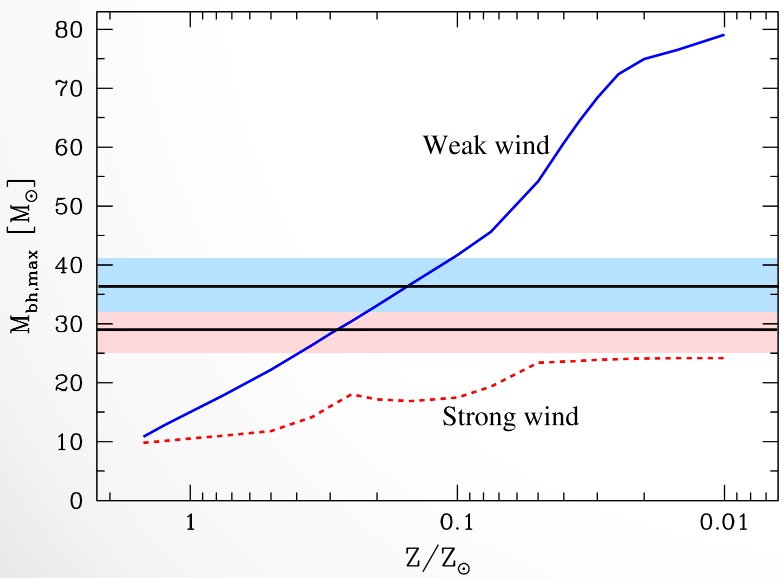
BBH merger rate

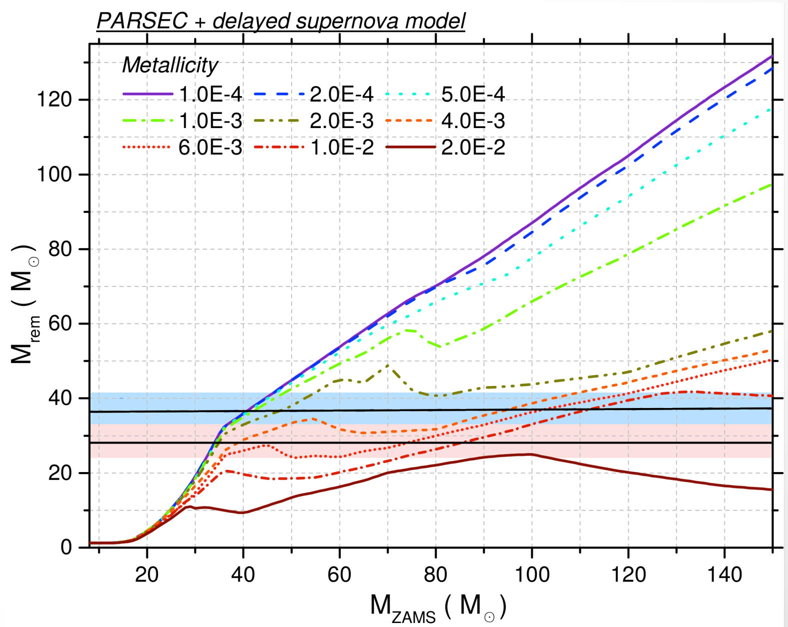


- Assuming constant volume up to horizon (z~0.5)
- For GW150914 type event R = 2 – 53 Gpc $^{-3}$ yr $^{-1}$
- Using all infos R = 2 – 400 Gpc $^{-3}$ yr $^{-1}$

How to form BBH ?

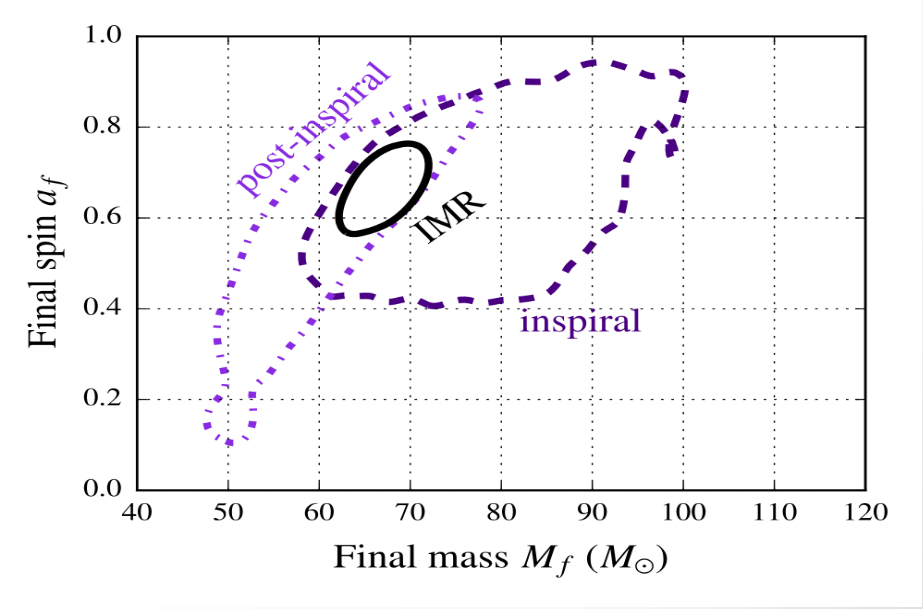
- Event observed is much heavier than what has been observed in X-rays binaries
- Not yet possible to distinguish between isolated binaries or capture in dense environment (globular clusters, galaxies center, …
- Favor low metallicity stars and then weak massive-stars wind





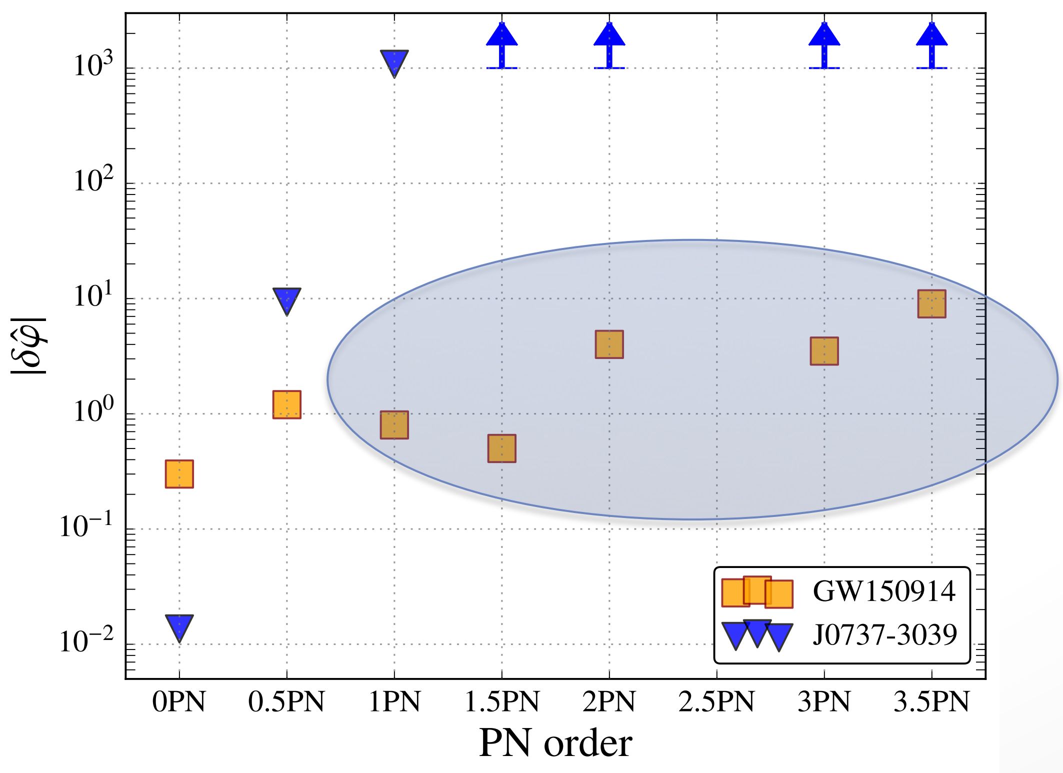
Testing General relativity in a new regime

- We have for the first time test under highly relativistic and non linear conditions
- Different tests can be peformed :
  - Remove waveform and see any deviation from noise in the data : possible deviations less than 4 %
  - Check the consistency of the waveform if:
    - Look only the pre merger phase
    - Use only the ringdown



Constraining parametrization deviations

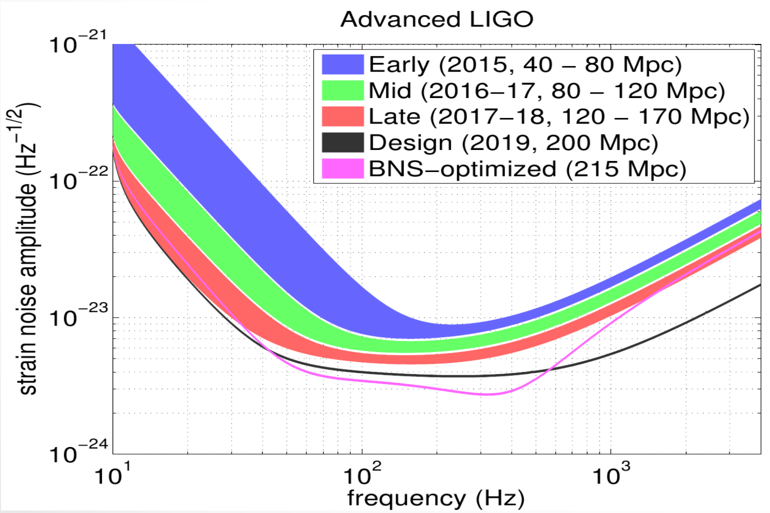
- We can test any non linear deviation to GR
- Using the complete waveform it then possible to test any deviation in the different orders of the post-Newtonian development of the waveforms with phase evolution

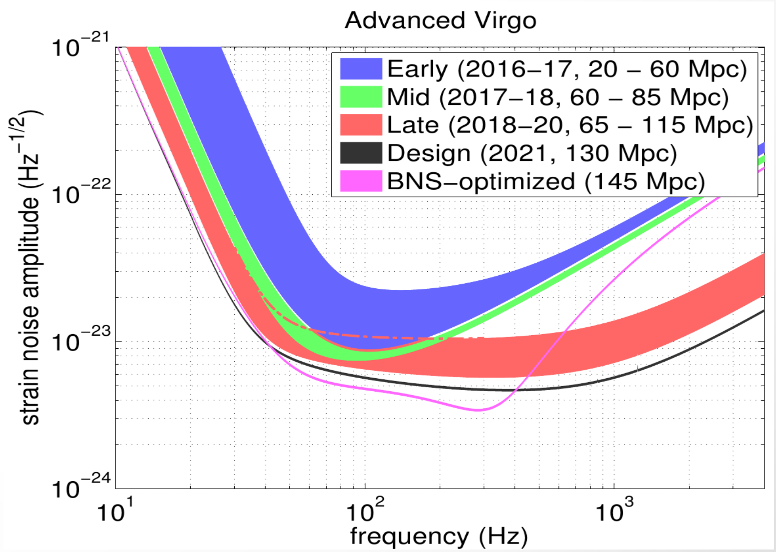


New regime !

LIGO and Virgo in the next months

- Next data taking this August – will extend up to beginning of 2017
- Virgo is still in construction and will try to join this run – maybe in fall 2016
- Third detector :
  - May increase number of sources (more up time with at least two detectors)
  - Improve sky localization if seen by the three : from x00 sq deg. to x0 sq deg.
  - One more measure is more constraints



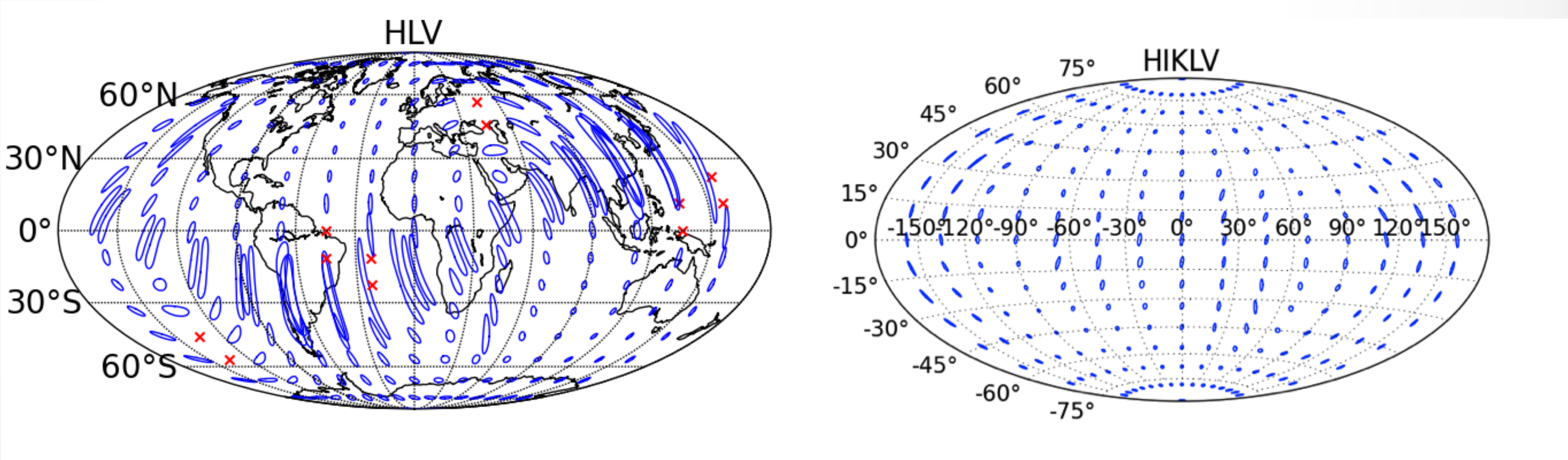


In terms of rates for BNS

Epoch	Estimated Run Duration	Burst Range (Mpc) LIGO	Burst Range (Mpc) Virgo	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within 5 $\deg^2$	% BNS Localized within 20 $\deg^2$
2015	3 months	40 – 60	—	40 – 80	—	0.0004 - 3	-	-
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 - 20	2	5-12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 - 100	1-2	10-12
2019+	(per year)	105	40 – 70	200	65 – 130	0.2 - 200	3-8	8-28
2022+ (India)	(per year)	105	80	200	130	0.4 - 400	17	48

New detectors not far away

- KAGRA is well advanced – we may have comparable sensitivity before 2018 (?)
- India recently accepted to host a LIGO interferometer, we may a 5th detector in 2020-2022



Comparison between 3 and 5 detectors for sky localization

At the end

- We have made the first direct detection of an astrophysical event with gravitational wave
- We have for the first time observed a binary black hole system and its merger
- We have observed an high mass binary system

  We are opening new ways to observe the Universe and its densest parts
  We will also be able to test GR in new regimes

- SVOM is already doing science !
- Time around 2020 will be very interesting for transient sky !