

Observation of Gravitational Waves from Binary Black Hole Mergers with Advanced LIGO Hanford and Livingston detectors



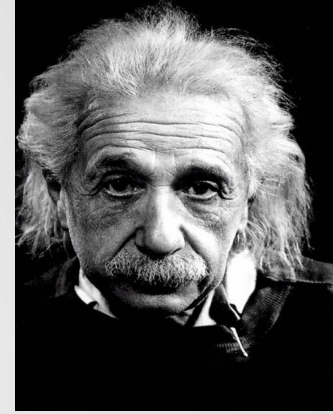
Nicolas Leroy on behalf of LSC and Virgo,
LAL CNRS/Université Paris-Sud



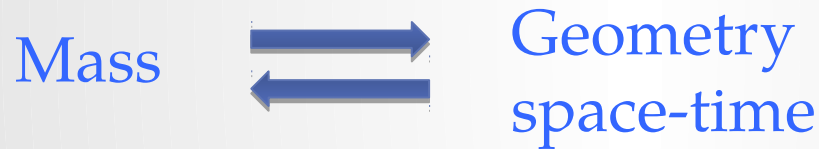
Overview

- General relativity, generation of Gravitational Waves and sources
- Experimental challenge
- The different detections
- What's next ?

General relativity

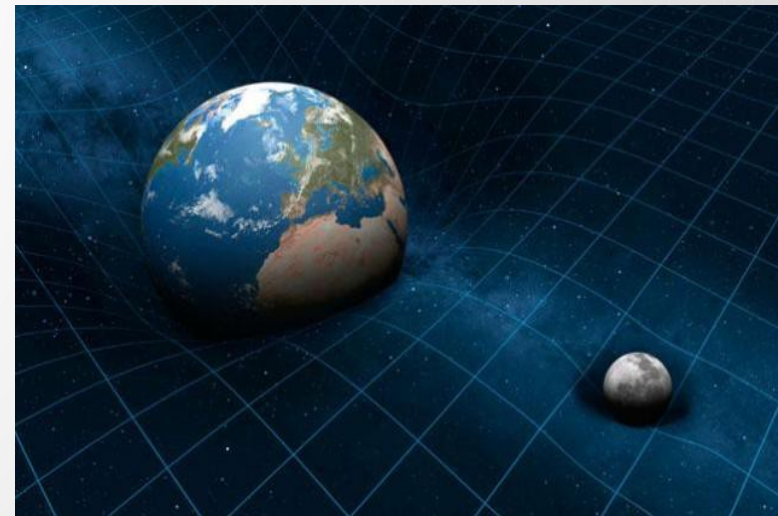


- Gravitation is a curvature of the space-time metric
- Any massive object will introduce a deformation of the metric

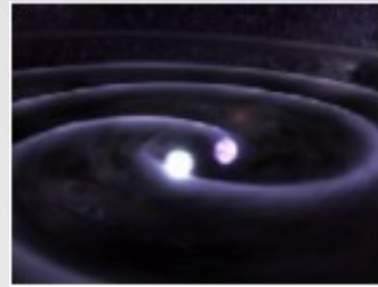


$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

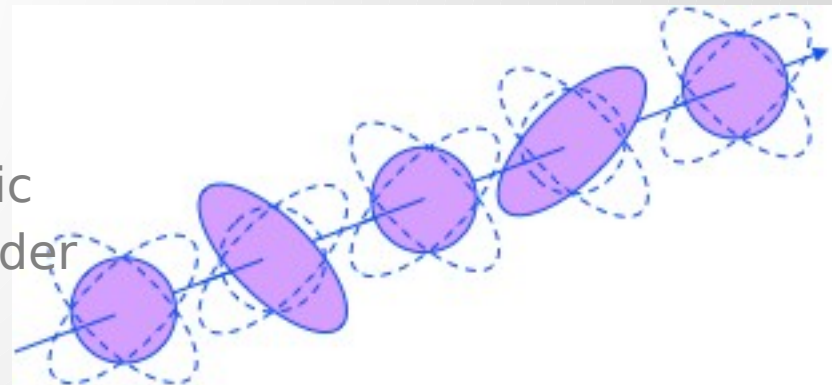
- Free falling objects will follow geodesics
- There is no absolute referential
- Widely tested/used



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



Compact and relativist

Source : mass M , size R , period T , asymmetry a $\blacktriangle$ $\ddot{Q} \approx a M R^2 / T^3$

Quadrupole formula becomes : $P \approx \frac{G}{c^5} a^2 \frac{M^2 R^4}{T^6}$

« G/c^5 very small , c^5/G will be better » @ J. Weber(1974)

New parameters

- characteristic speed v
- Schwarzschild Radius $R_s = 2GM/c^2$

$$P \approx \frac{c^5}{G} a^2 \left(\frac{R_s}{R} \right)^2 \left(\frac{v}{c} \right)^6$$

Needs to have

- Compact object : $R \sim R_s$
- Relativist : $v \sim c$
- asymmetric

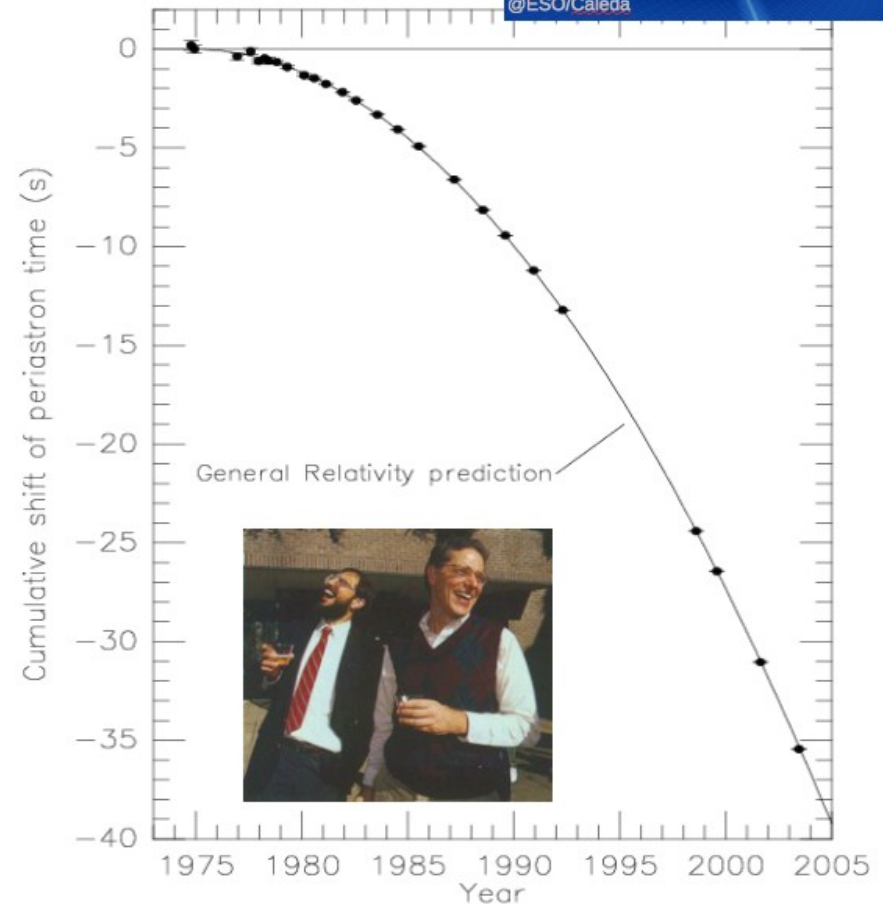
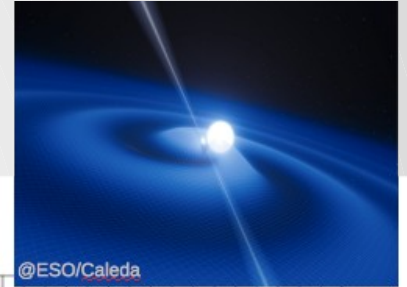


Neutron star (NS)
Black hole (BH)

Deformation @ Earth $< 10^{-18}$ m

Clues on their existence

- Observation done from binary pulsars
- Such system will loose energy due to GW emission
- Change in orbital period
- One beautiful example is PSR1913+16
- Observed for more than 30 years
- Nobel Prize in 1993



A century of progress

Theoretical developments

Experiments

📅 **1916: GW prediction (Einstein)**

1957 Chapel Hill Conference

(Bondi, Feynman, Pirani, etc.)

📅 **1963: rotating BH solution (Kerr)**

📅 **1960's: first Weber bars**

📅 **1970: first IFO prototype (Forward)**

📅 **1972: IFO design studies (Weiss)**

📅 **1974: PSRB 1913+16 (Hulse & Taylor)**

📅 **1980's: IFO prototypes (10m-long)
(Caltech, Garching, Glasgow, Orsay)**

📅 **1990's: CBC PN expansion
(Blanchet, Damour, Deruelle,
Iyer, Will, Wiseman, etc.)**

📅 **1990's: LIGO and Virgo funded**

📅 **2005-2011: initial IFO « science » » runs**

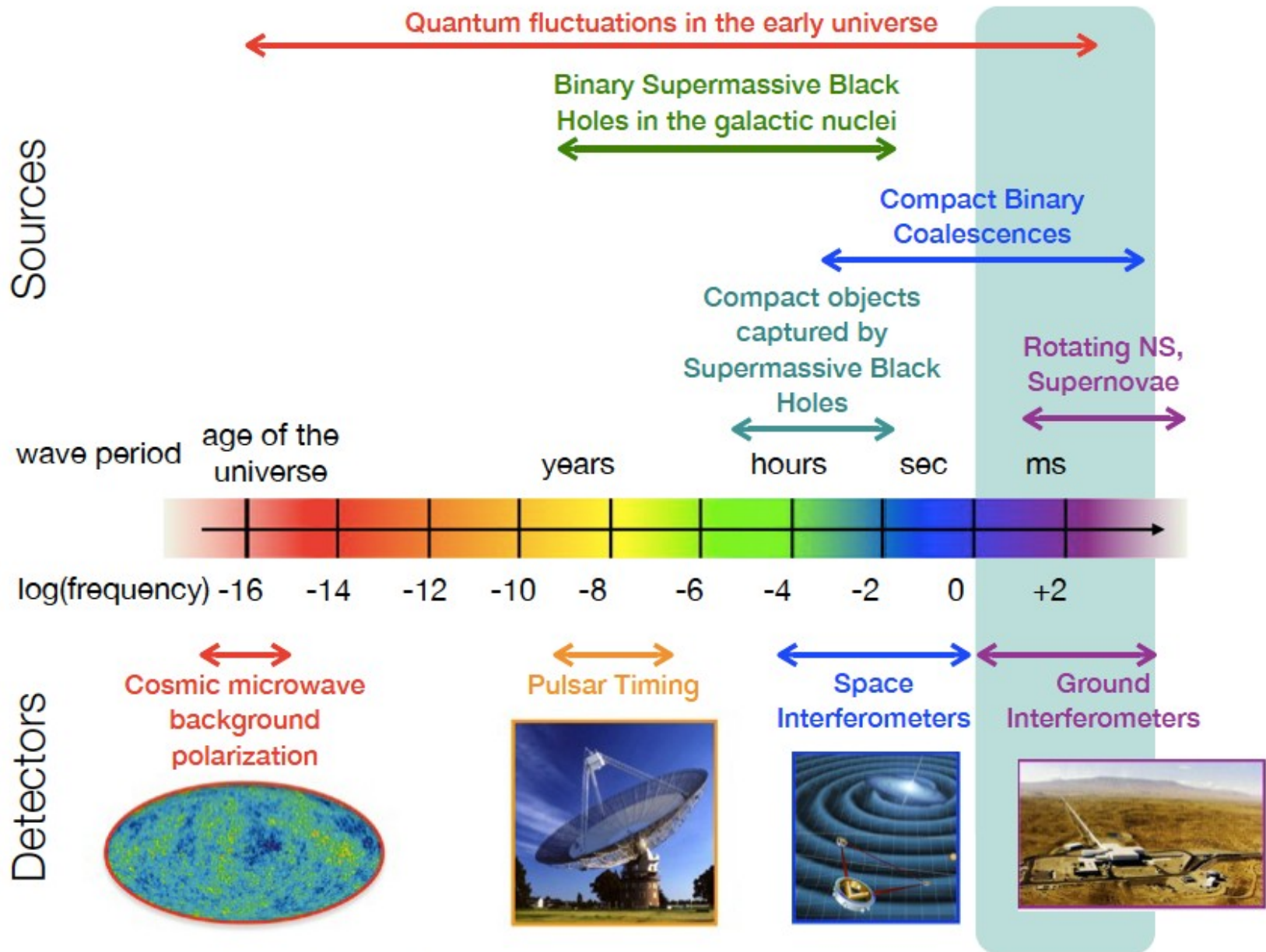
📅 **2000: BBH effective one-body
approach (Buonanno, Damour)**

📅 **2007: LIGO-Virgo Memorandum
Of Understanding**

📅 **2006: BBH merger simulation
(Baker, Lousto, Pretorius, etc.)**

📅 **2015: First Advanced LIGO science run**

The Gravitational Wave Spectrum

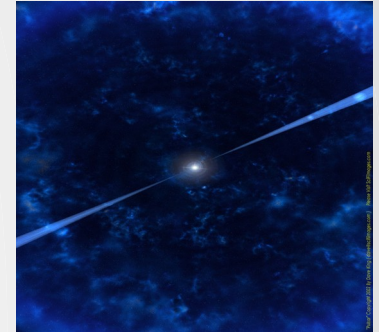
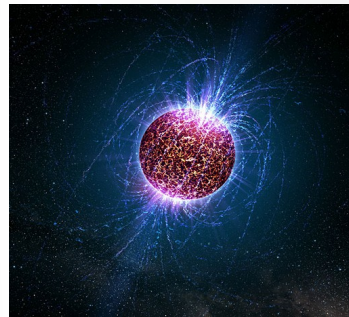
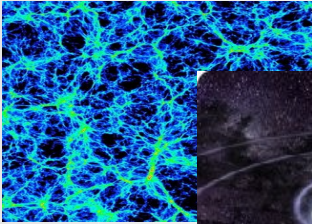


GW zoology

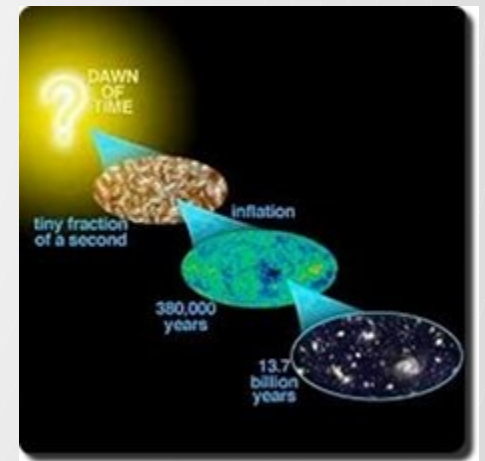
Short duration (1sec)

Long duration (∞)

Waveform
known



Waveform
unknown

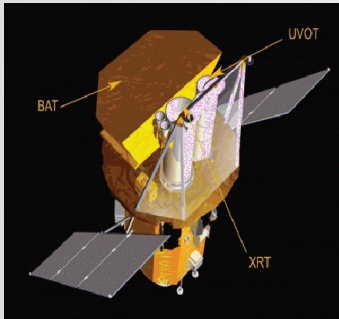


Multimessenger astronomy

Gamma-rays



X-rays

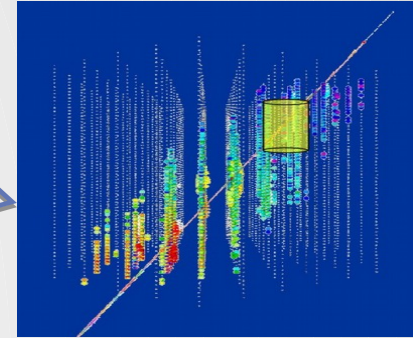


Optical



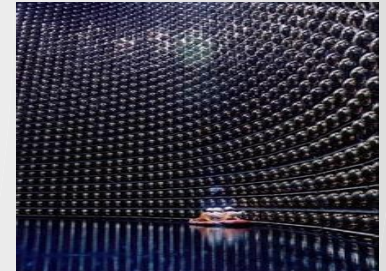
GRB

HE (>1 TeV) ν



Supernovae
type II

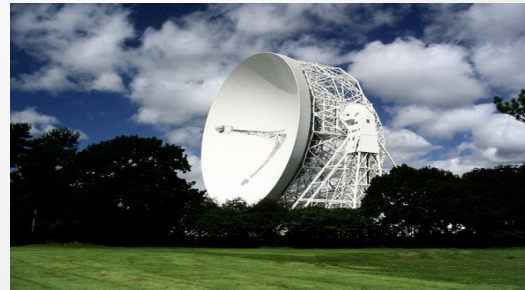
LE (MeV) ν



SGR/AXP

Giant Flare

Pulsar/
pulsar glitches



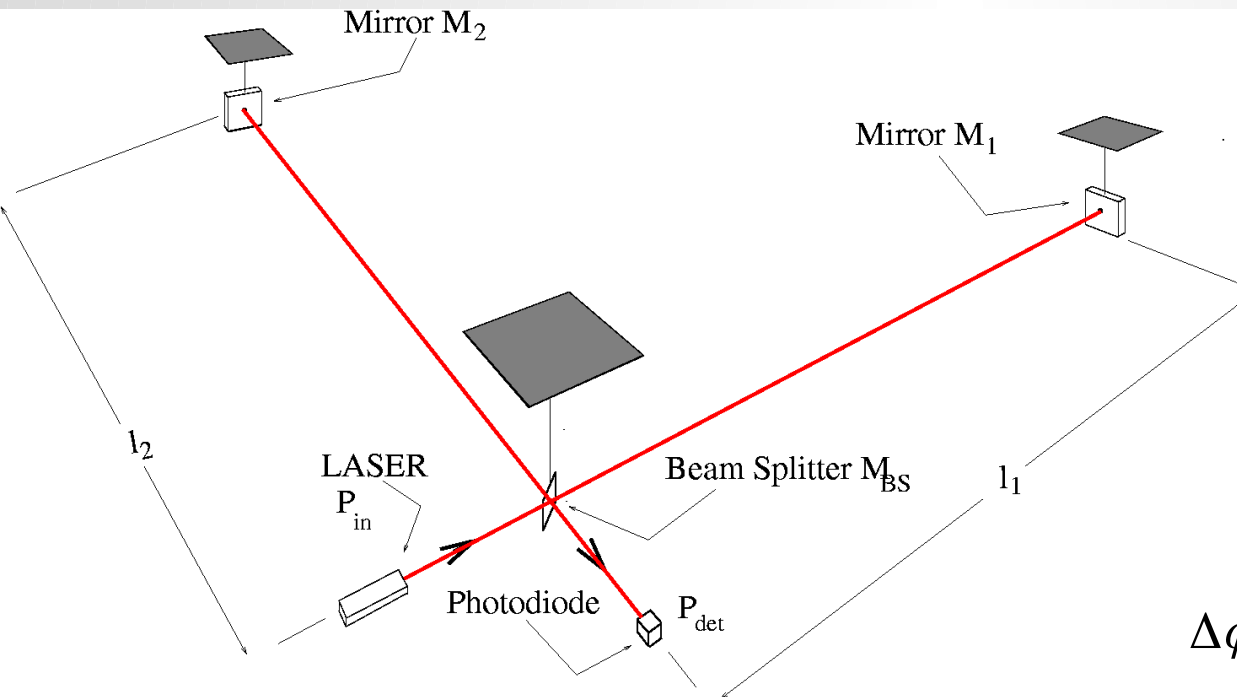
Radio

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 (on progress)
- Direct detection of black hole 
- Probe progenitor for GRB
- Test equation of state of neutron stars
- Provide constraints on stellar population (on progress)
- Cosmology : Hubble constant, primordial universe
-

Suspended interferometer

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



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

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

$$\Delta\phi = \frac{2\pi(l_2 - l_1)}{\lambda} + \frac{2\pi(l_2 + l_1)}{\lambda} h(t)$$

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

Main challenges for a detector on Earth

- Maximizing length of the detector -> kilometric optical cavities
- Avoid perturbation on optical path -> everything under high vacuum ie 7000 m³ for Virgo
- Mirrors as free falling masses ie decoupled from external perturbations -> suspended optics
- Precise control of the length between the different suspended optics
- Precise ruler -> stable high power laser both in power and frequency
- Reduce at maximum technical noises

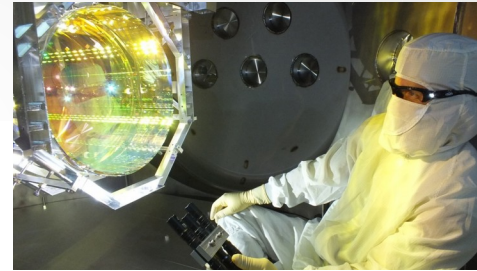
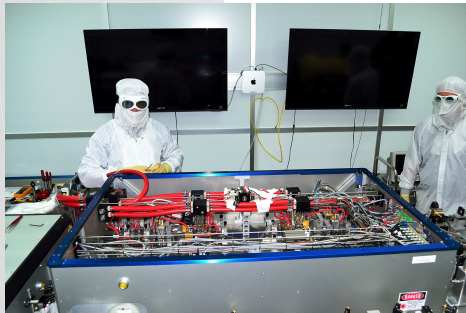
Advanced generation !

Michelson interferometer

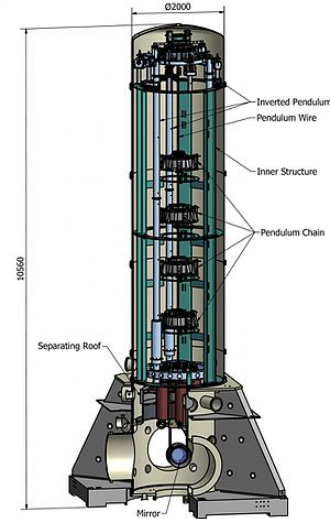
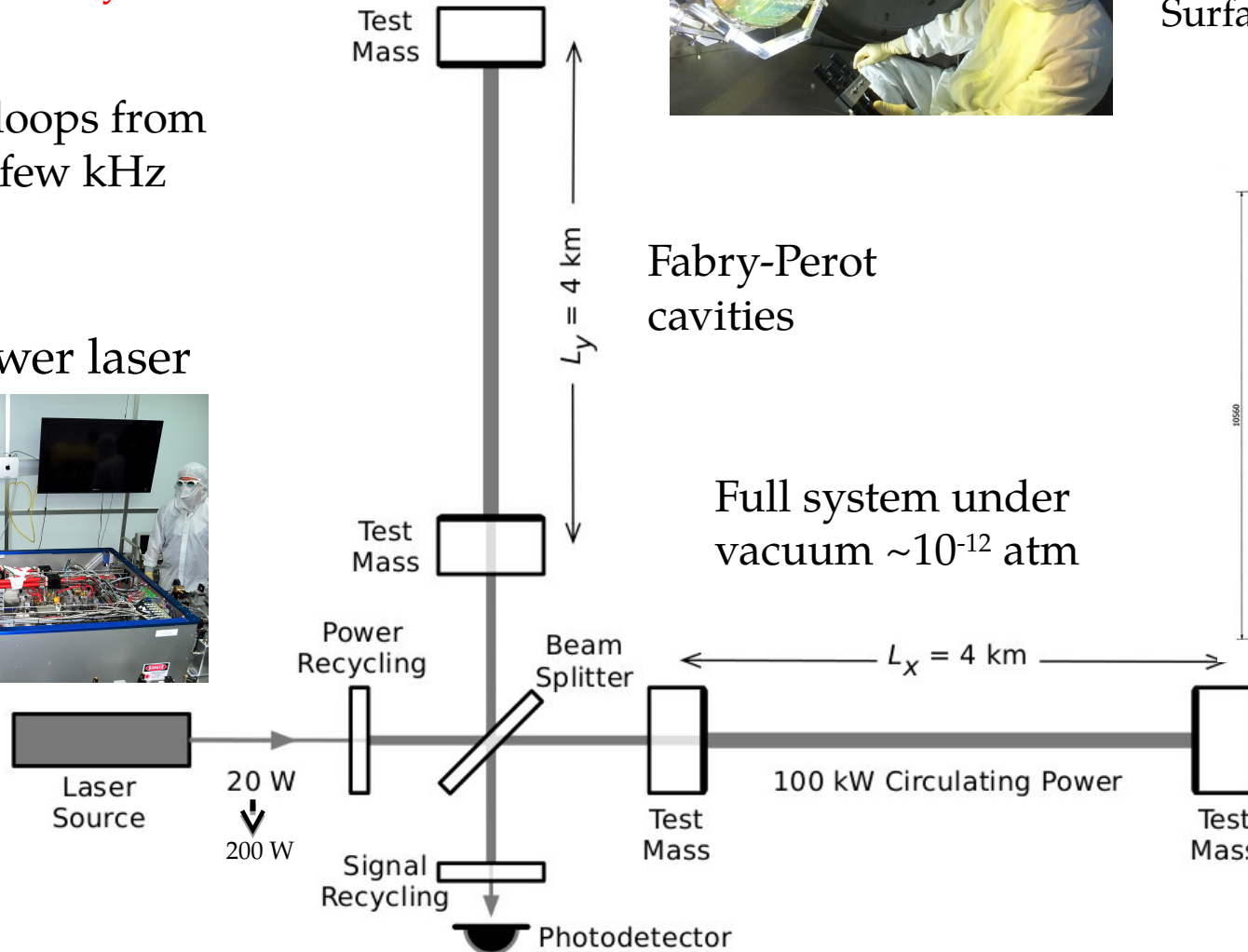
Goal : $(L_x - L_y)/L_x = 10^{-23}$

Feedback loops from
few Hz to few kHz

High power laser



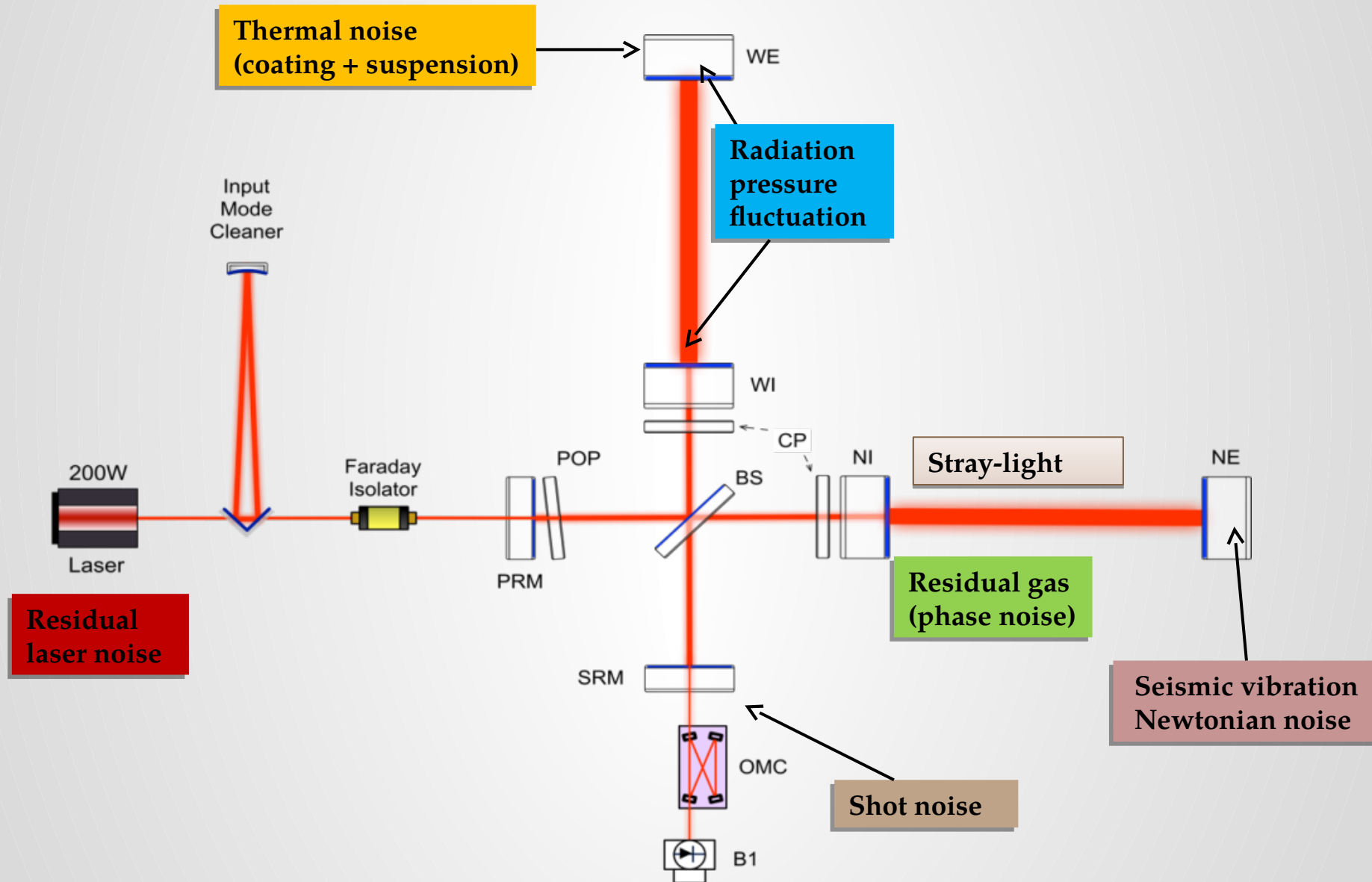
High quality
optics – 40 kg
Surface RMS ~nm



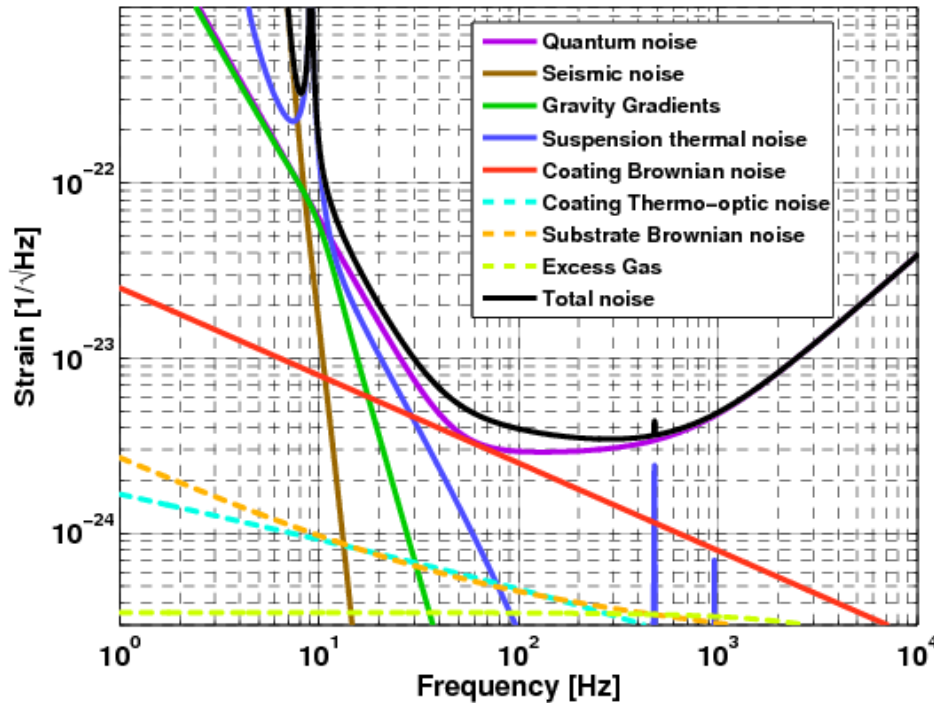
Suspended
Optics

Attenuation
 $10^{14} @ 10 \text{ Hz}$

Main sources of noise



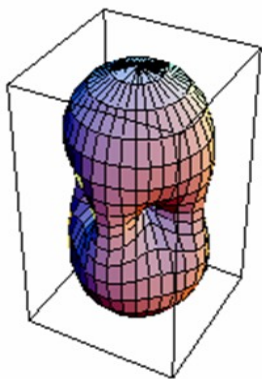
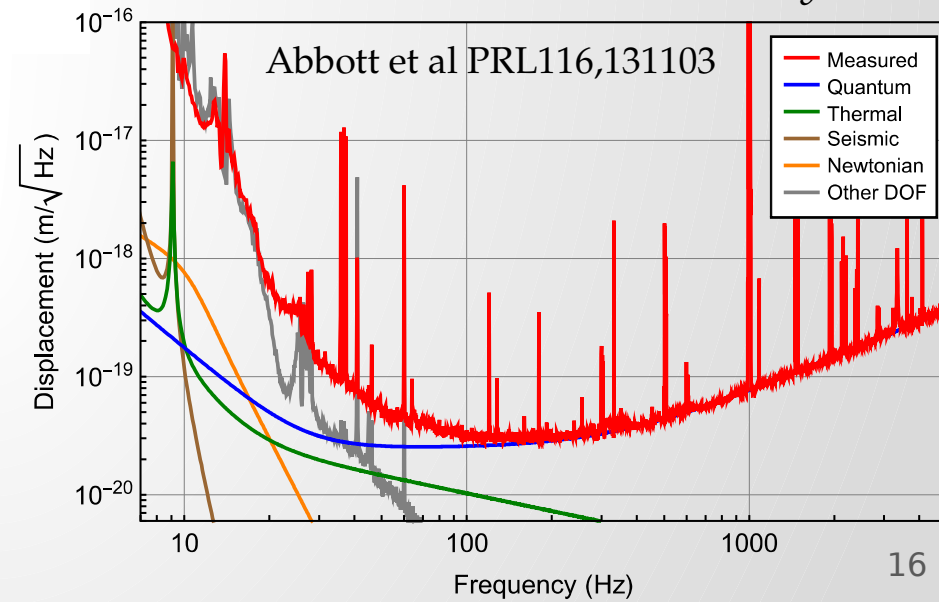
Sensitivity



Quantum noise =
error on phase measurement +
fluctuation of radiation pressure

Thermal noise Brownian
motion of the suspension,
mirror and coating on the
surface of the mirror

AdLIGO O1 sensitivity



unpolarized

Almost full sky
instruments

The GW detectors networks

LIGO –
Hanford 4-km

LIGO

GEO 600m

GEO

Virgo 3-km

VIRGO

Full ITF in 2020

KA RA

LIGO India

4-km in 2020-22



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

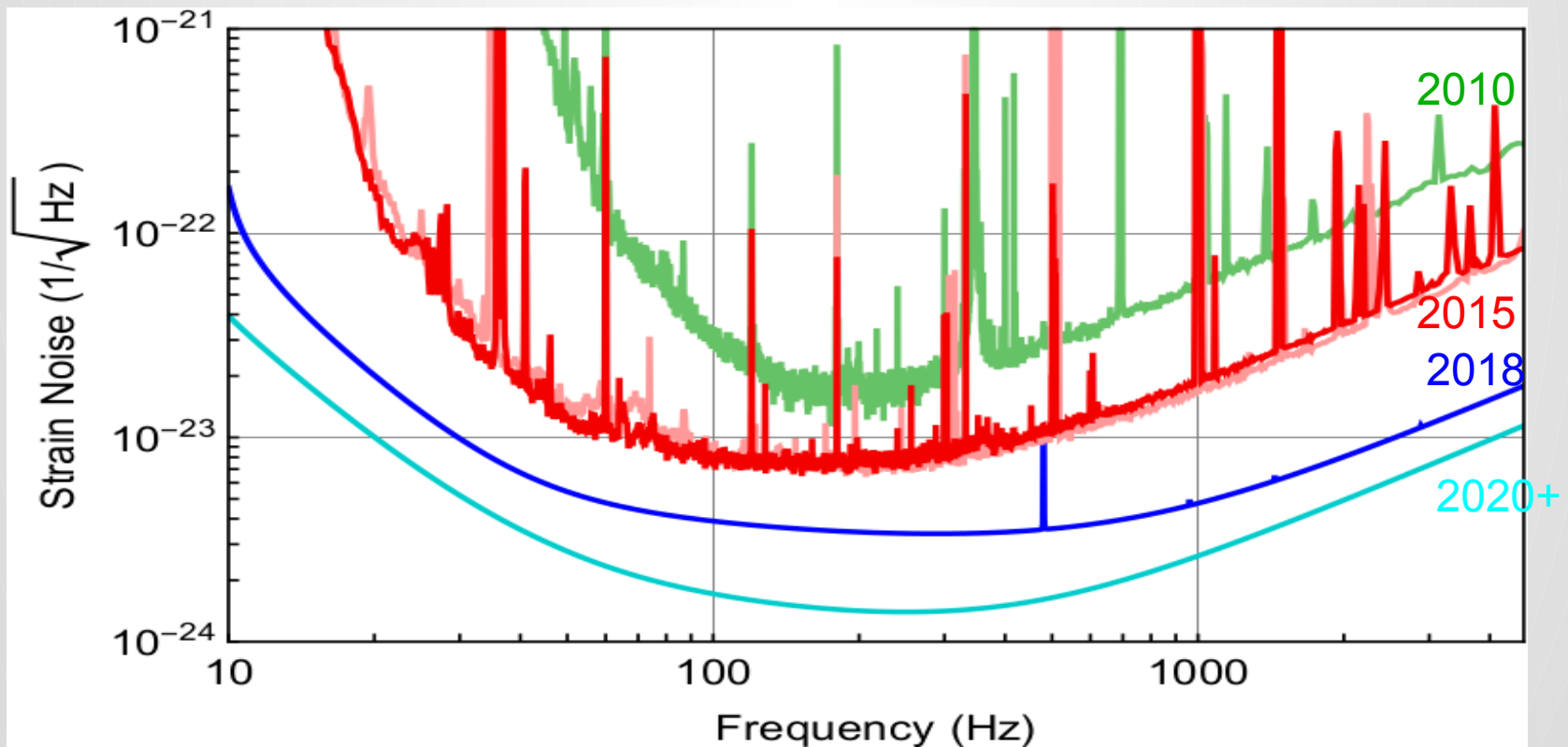
Virgo

5 countries – 200 contributors

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

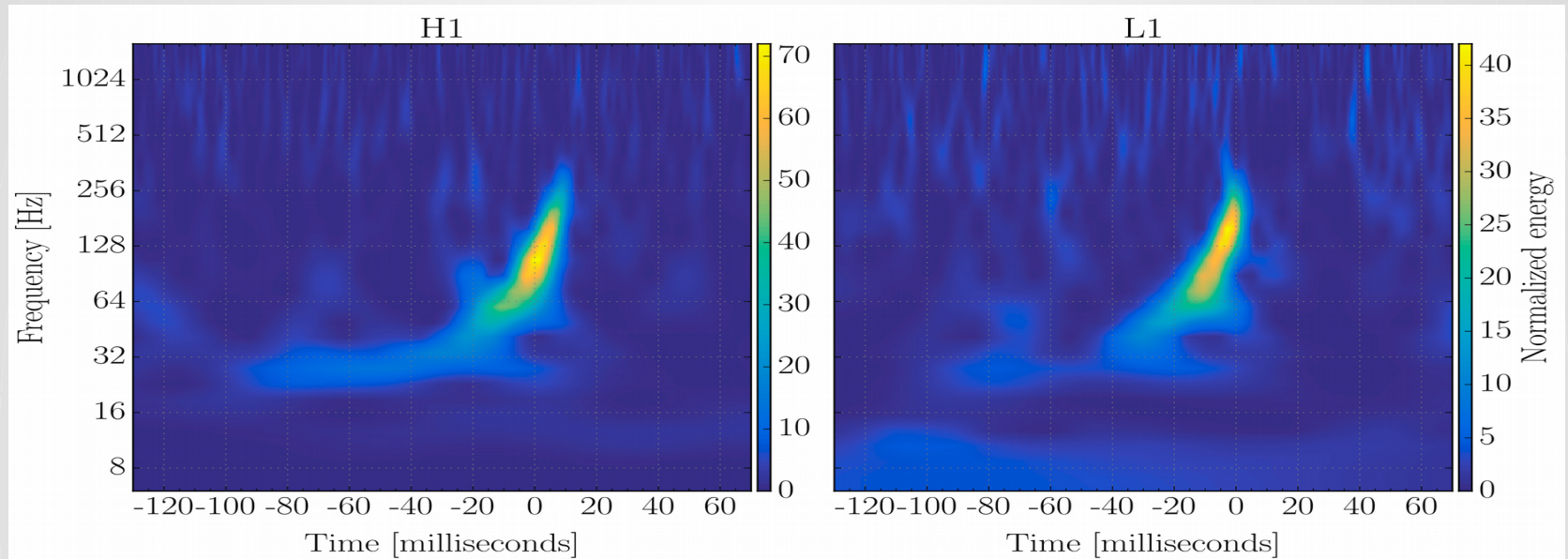
Advanced LIGO run 01

- 2010-2014: installation
- 2014-2015: commissioning
- September 2015: O1 run start!
End Jan 19th 2016
- Horizon (BNS): 70 – 80 Mpc
- 3-4 times more sensitive than LIGO
- 30-60 times larger in volume



The 14th of Septembre 2015

Abbott *et al.* PRL 116, 061102



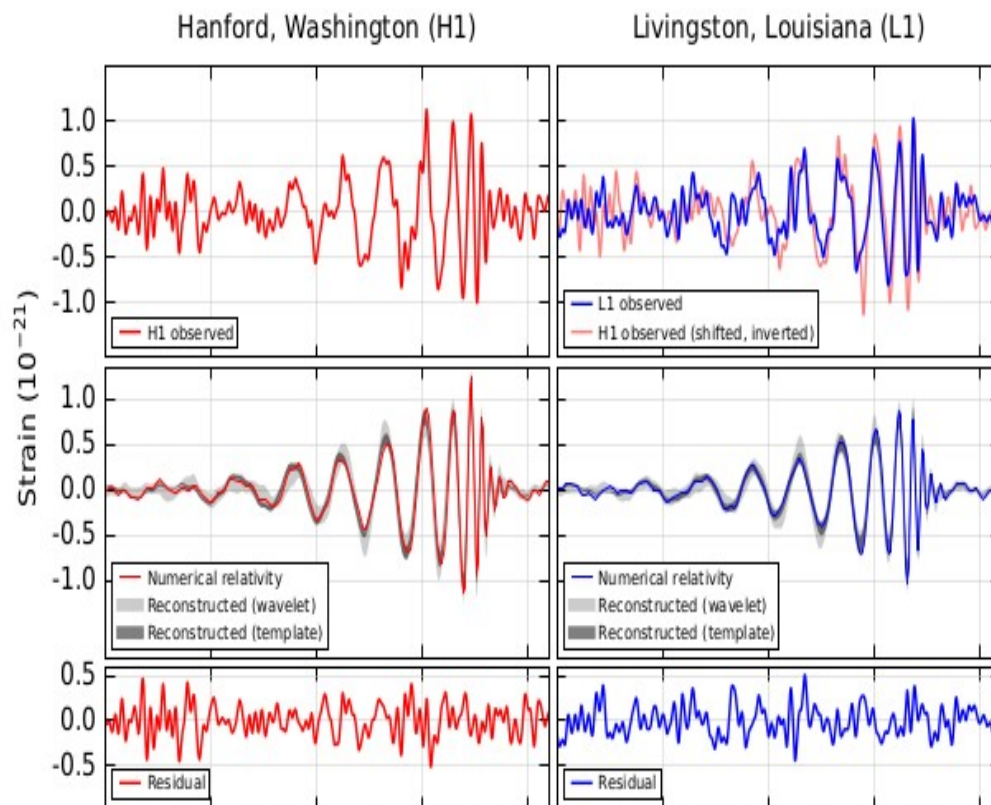
- Event reported within 3 minutes by an unmodelled search
- Within one hour, first (of a very long list) email reporting an interesting event
- In less than two hours nature and first parameters derived : BBH !!!
- Very low false alarm probability reported – message from directorate : this is not an 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)

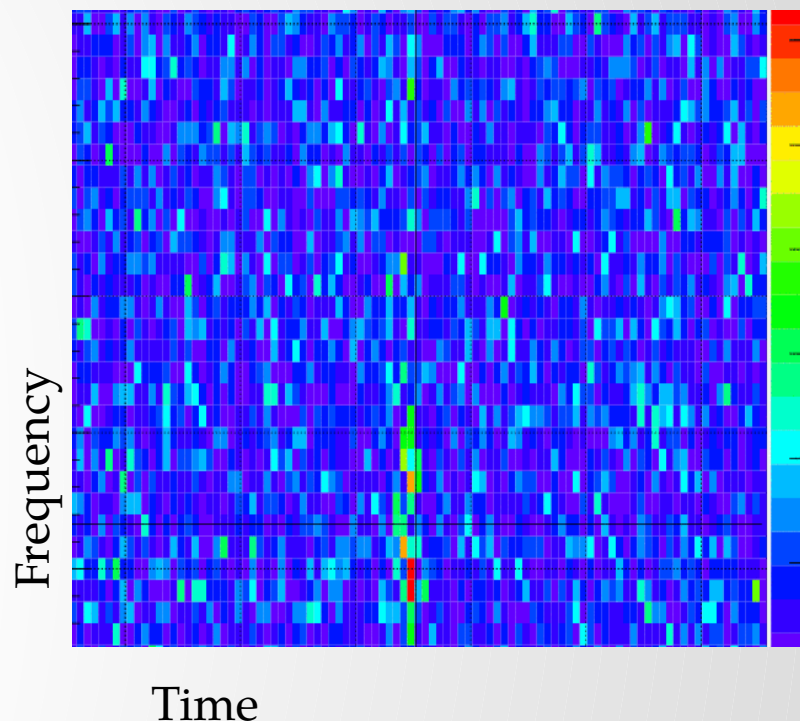
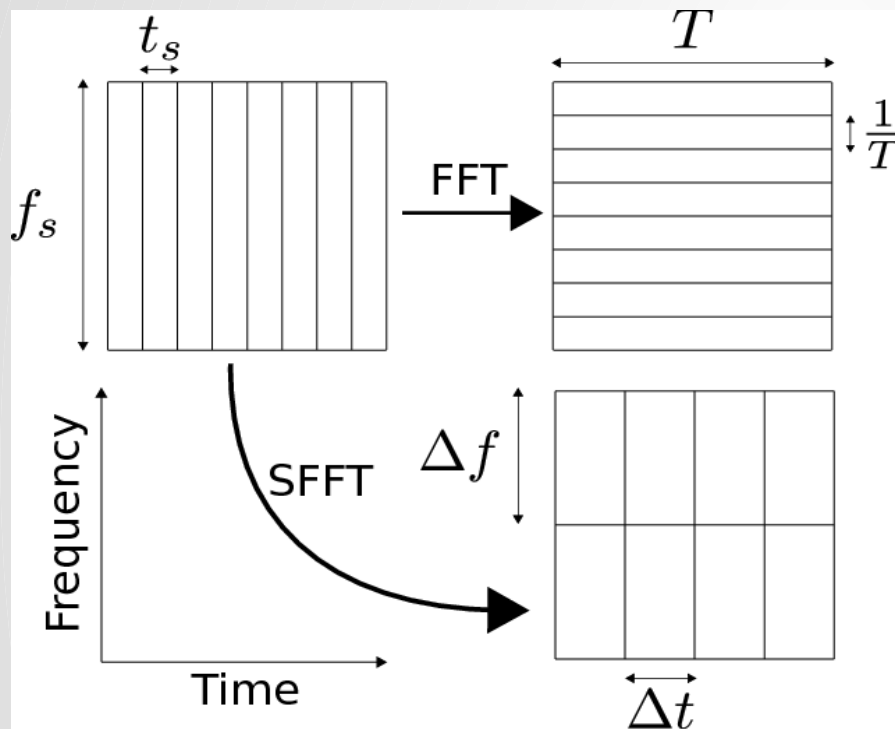
Third Row –residuals



Abbott *et al.* PRL 116, 061102

ie

Looking for unmodelled signal



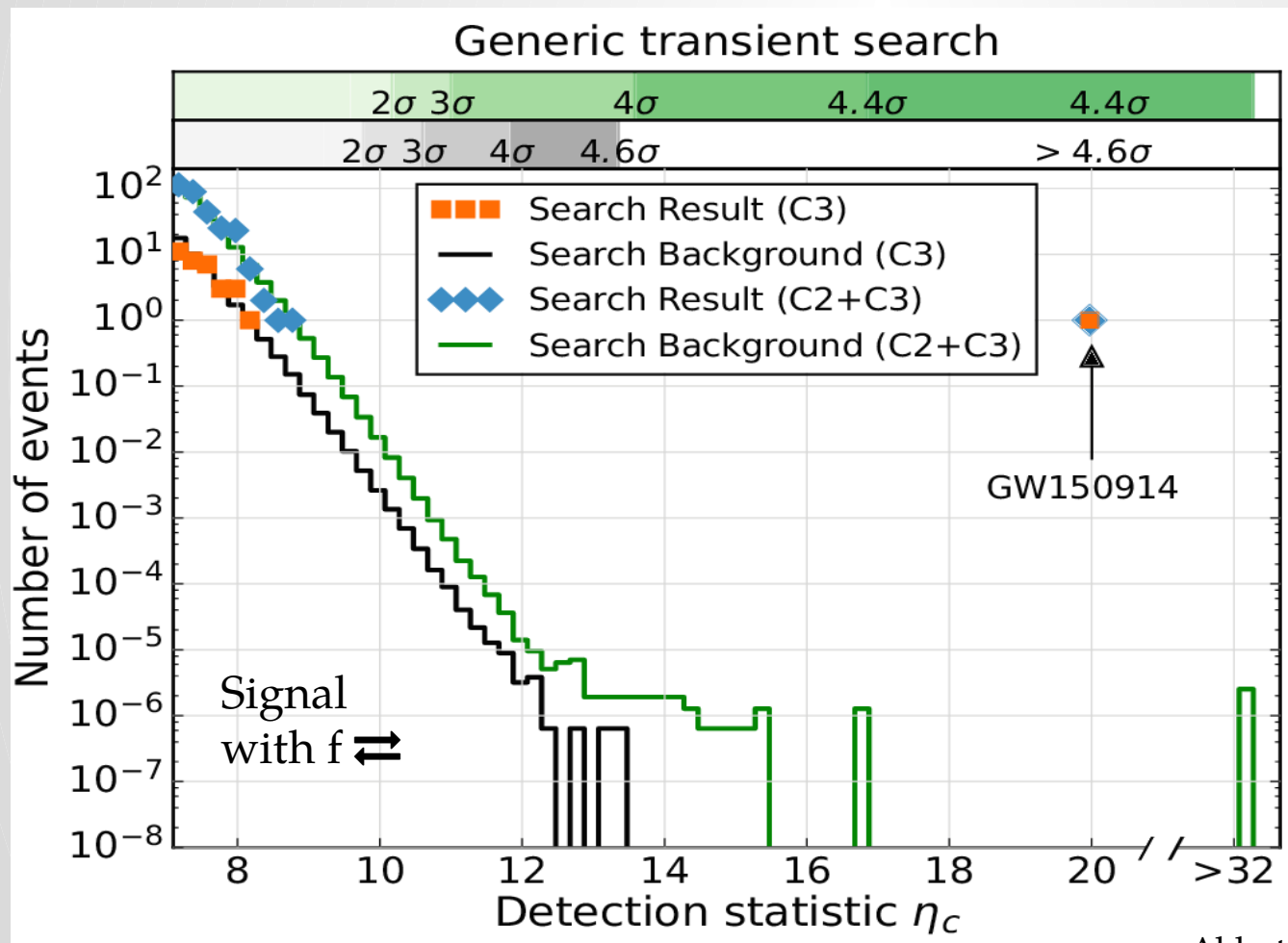
Excess in time-frequency map – using wavelet
 Similar efficiency for high mass binaries ($< 10 \text{ Msun}$)
 Was running online
 Background estimation with timeslides

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.
< $2 \cdot 10^{-6}$ - > 4.6 σ

Abbott *et al.* PRL 116, 061102

Search for modelled waveform

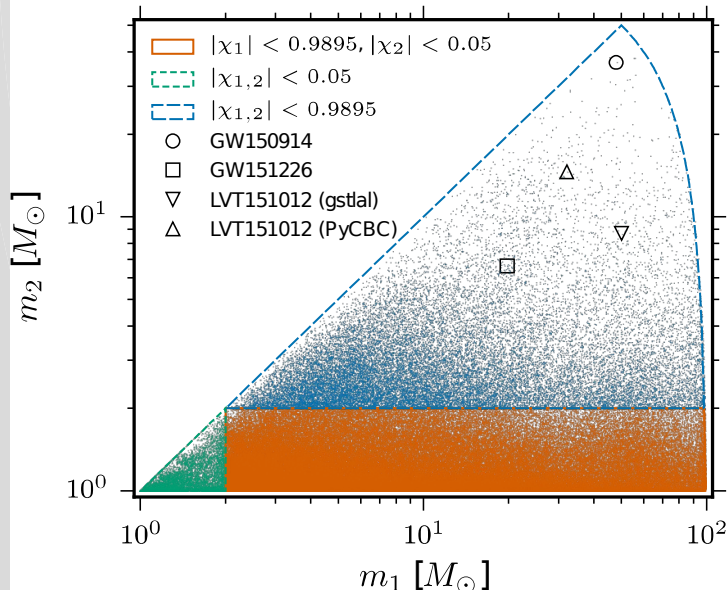
FFT of data

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)

Abbott et al, PRX 6 041015 (2016)



September 2015 configuration:

Waveform templates: EOBNR with aligned spins

Online: low mass regime (<20 Msun) then move to full set in October

Offline: 1-100 Msun – 250 000 templates

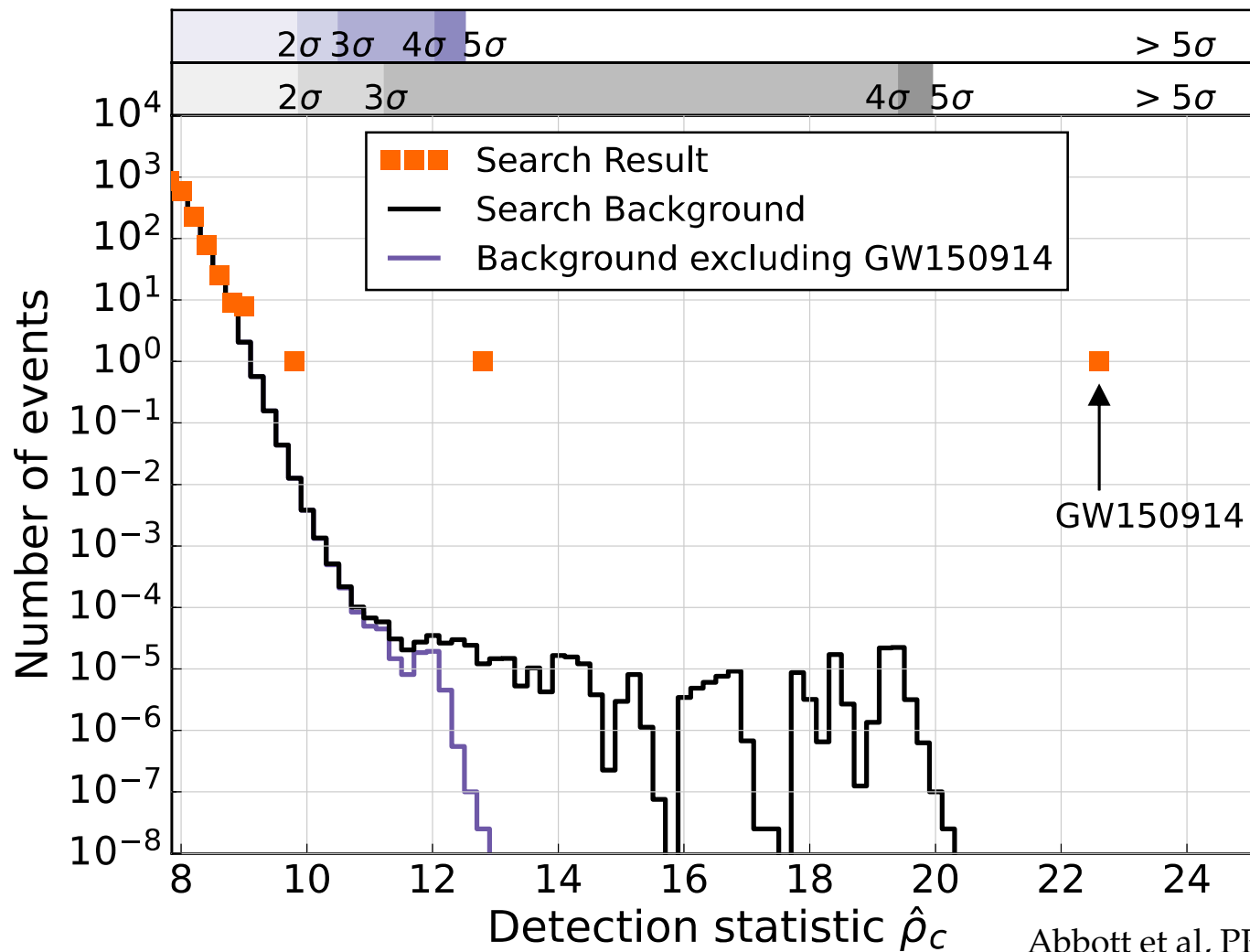
Chi2 test with best match template – coincidence 15 ms

Calculate quadratic sum of SNR in each detector

Background estimation done with time slides

Results for BBH search during O1

using match filtering



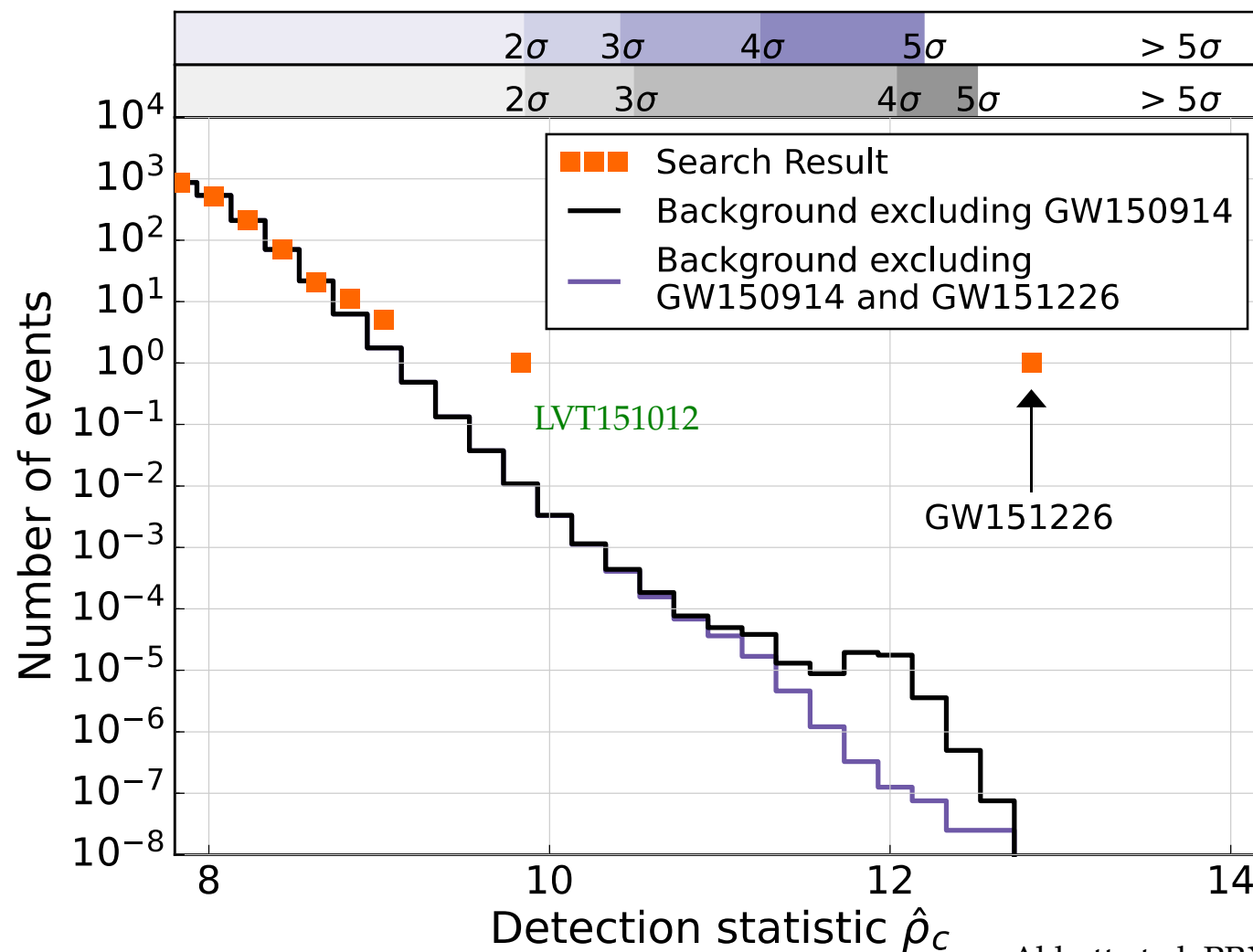
False Alarm Rate
 $< 1 / 200\,000$ years

False Alarm Prob.
 $< 1.1 \cdot 10^{-7} - > 5.3 \sigma$

Abbott et al, PRX 6 041015 (2016)

Results for BBH search during O1

using match filtering



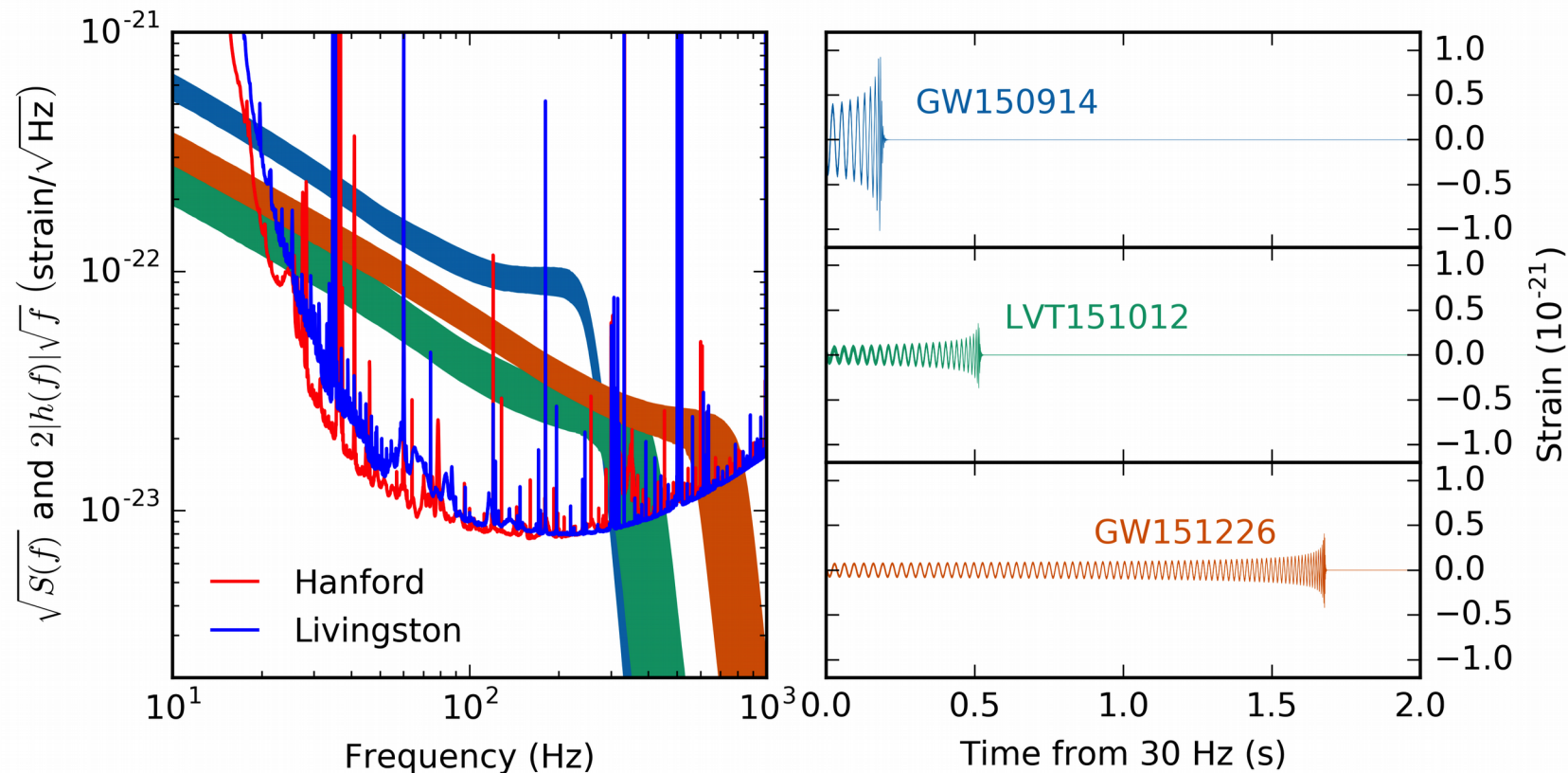
False Alarm Rate
 $< 1 / 200\,000$ years

False Alarm Prob.
 $< 1.1 \cdot 10^{-7} - > 5.3 \sigma$

LVT151012
 1.7σ

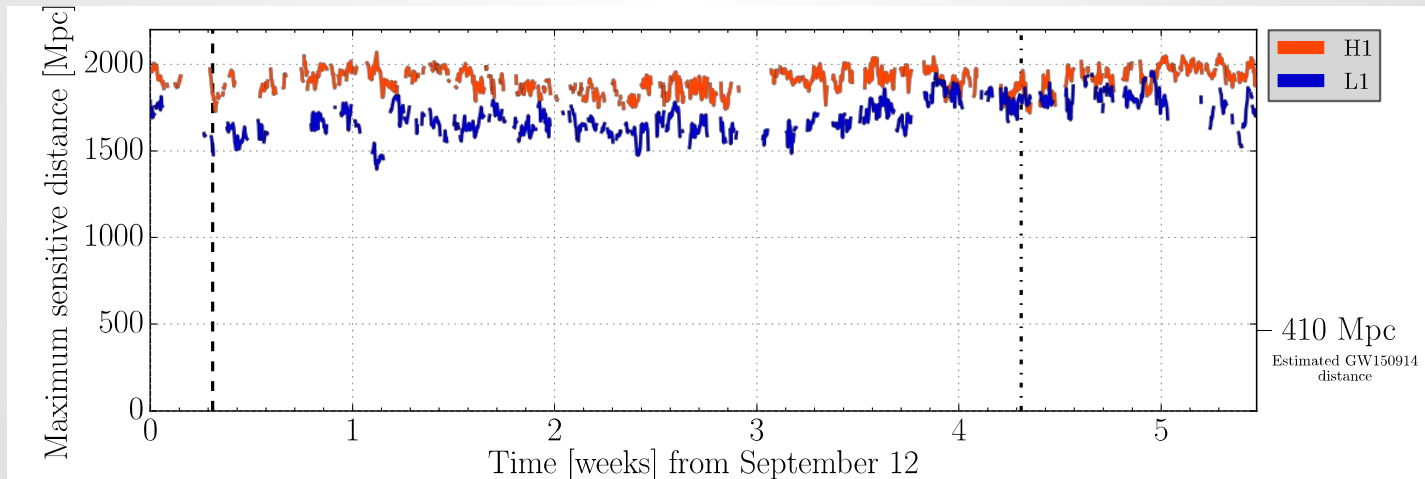
Comparing the signals

Abbott et al, PRX 6 041015 (2016)



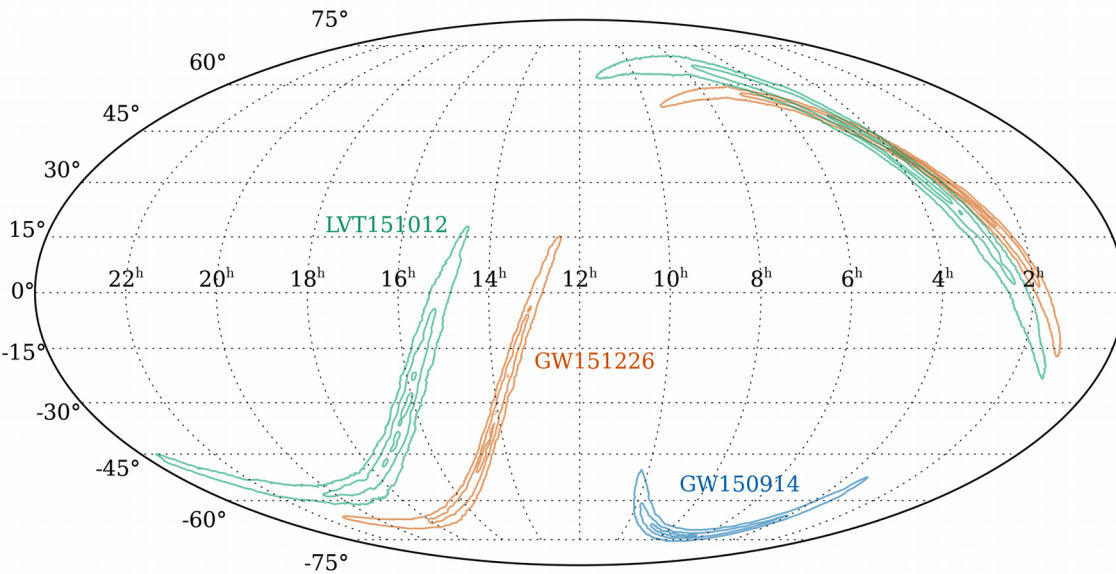
Can it be something else?

- **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 around the events



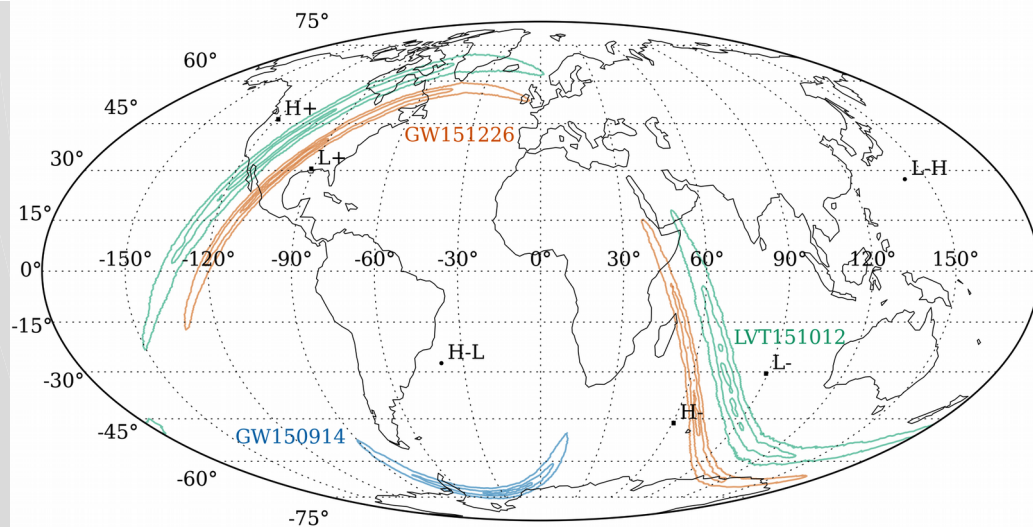
Sky location

Abbott et al, PRX 6 041015 (2016)



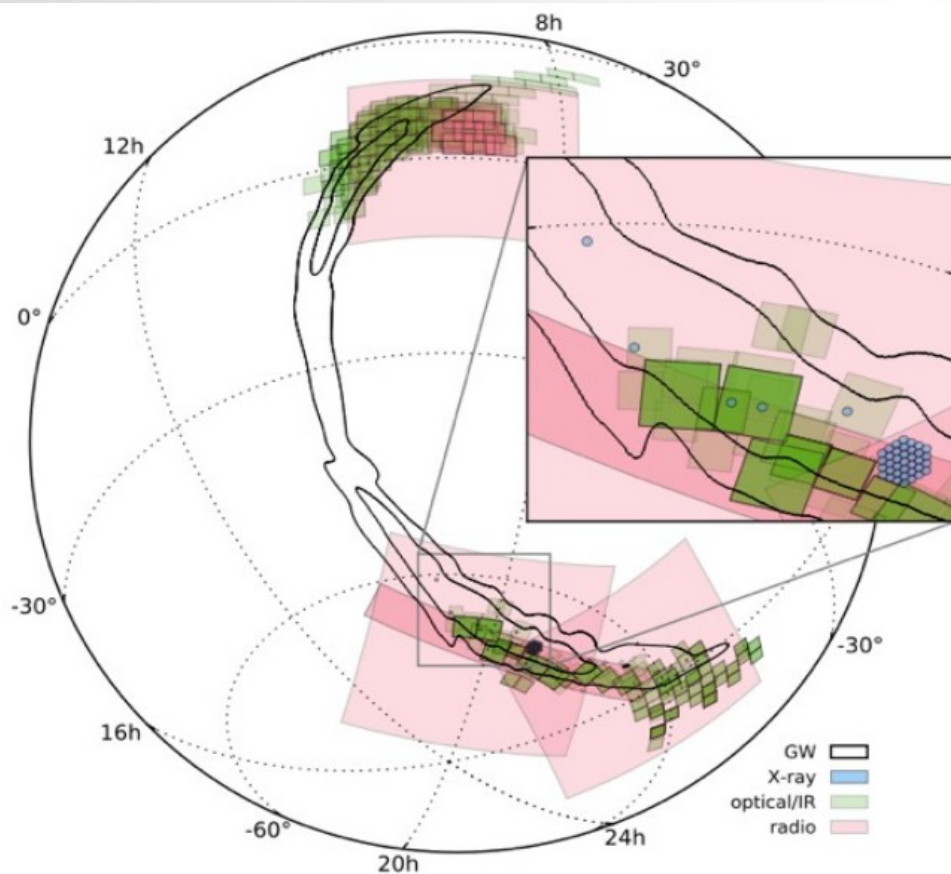
230 sq deg
850 sq deg
1600 sq deg

different pipelines with
different assumptions got
similar results

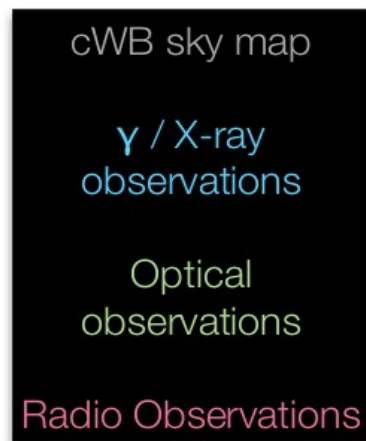


Follow-up with external observatories

Abbott *et al.* ApJL vol. 826 pg. L13



GW150914 alert sent to a private network first event sent with 48 hours of delay
Followed up by 21 teams

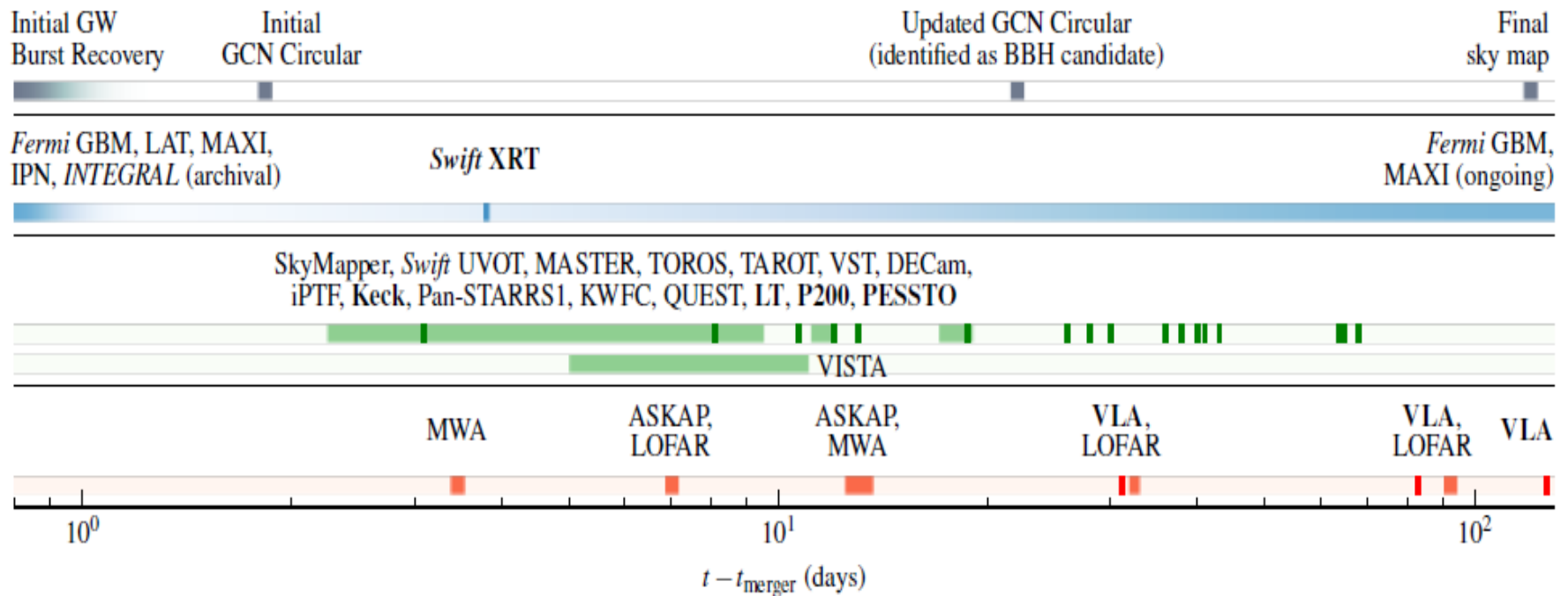


External observatories first focus on BNS systems

Follow-up with external observatories

Abbott *et al.* ApJL vol. 826 pg. L13

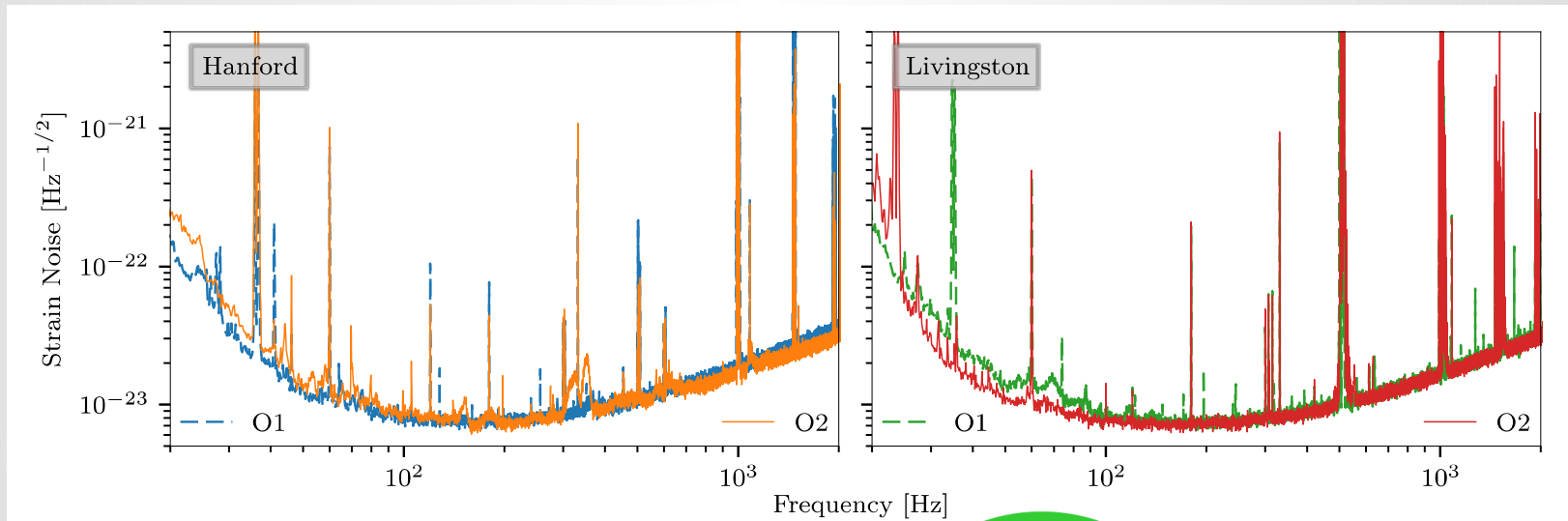
GW150914 example



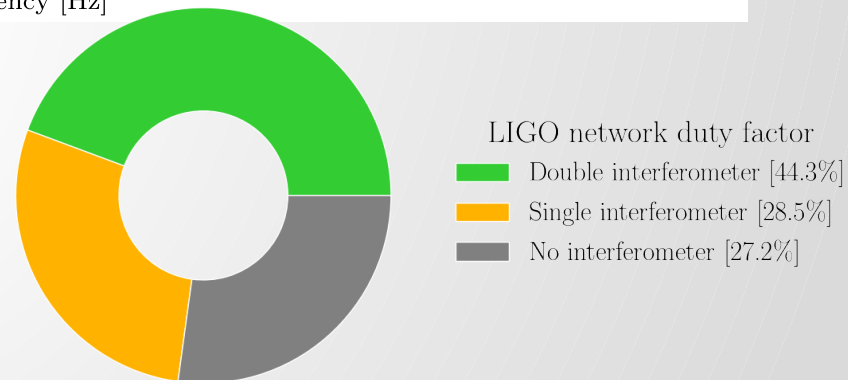
No clear signal yet reported

O2 run

- Began 30th of November 2016 still in progress, end date 28th of August 2017
- Sensitivity quite similar to O1 run

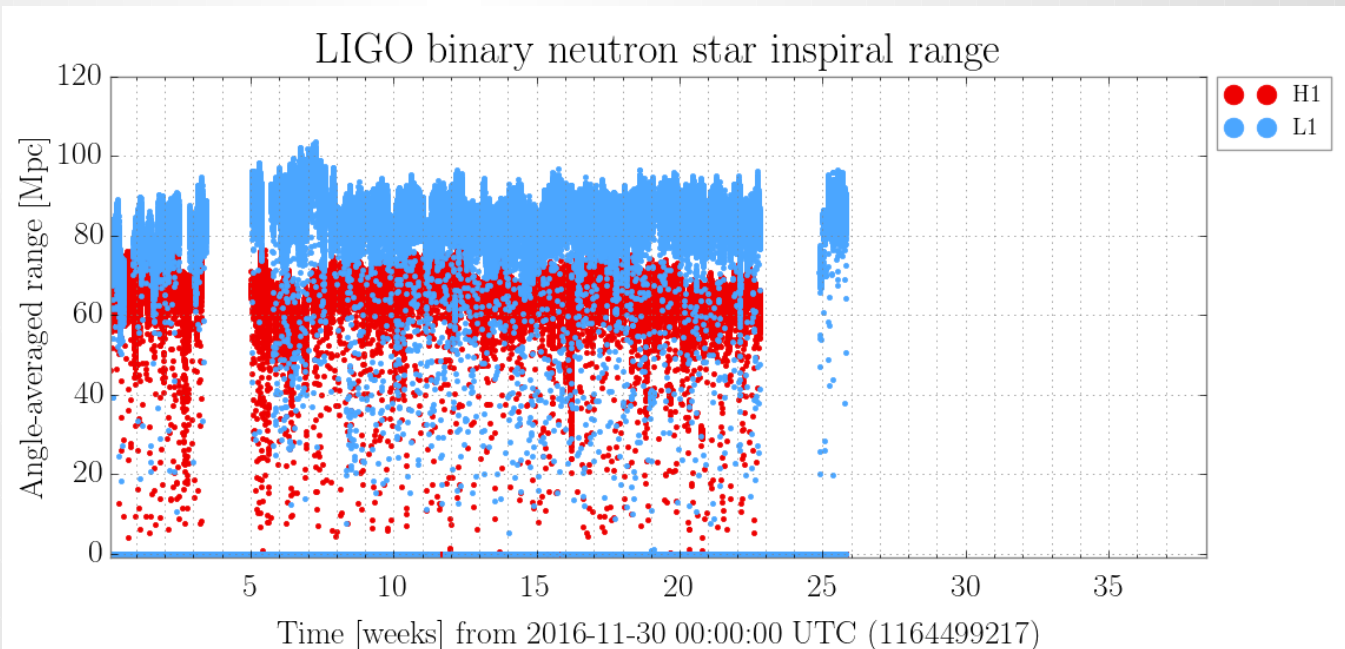


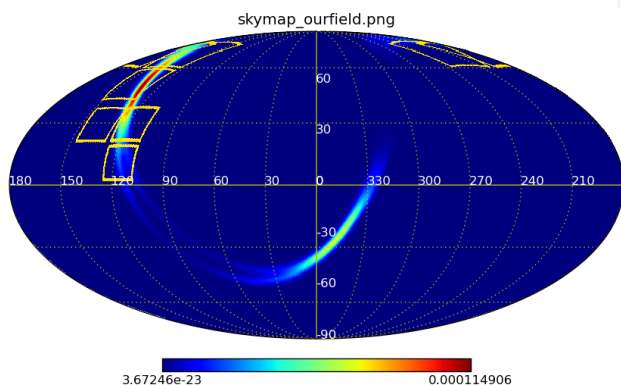
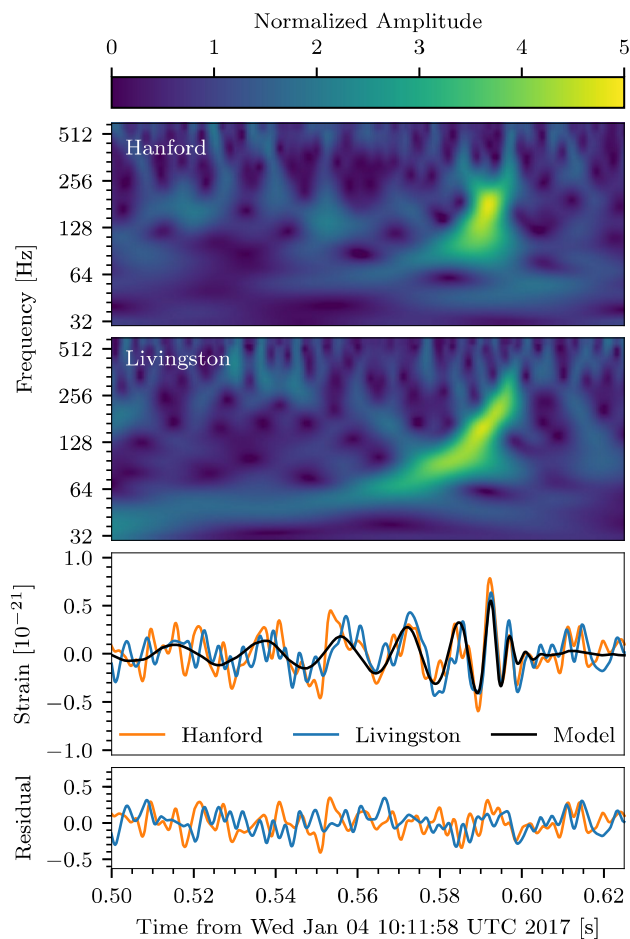
- Duty cycle 2 ITFs : 45 %



O2 range and alerts

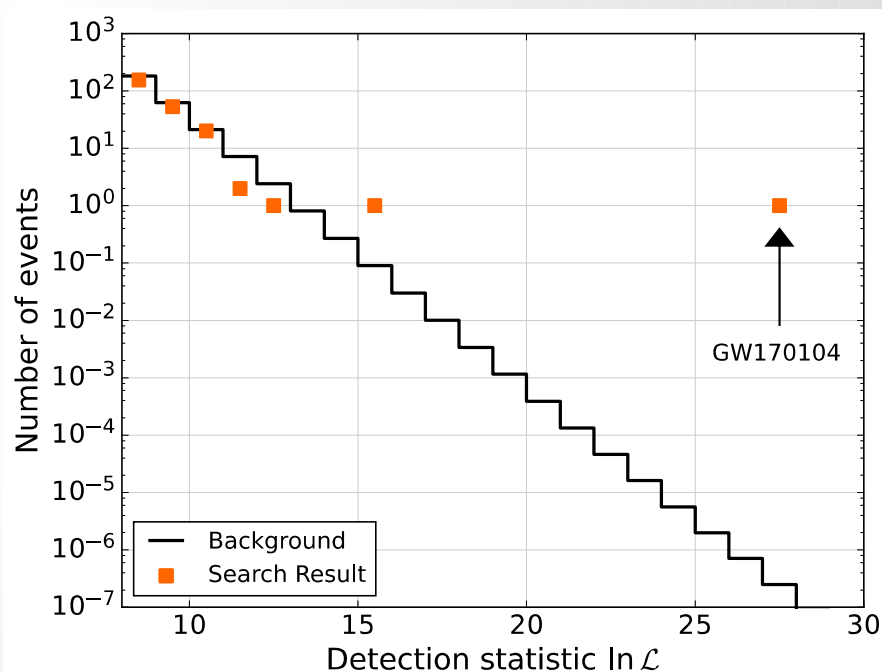
- Average reach of the LIGO network
 - BNS ~ 70 Mpc
 - BBH (10 solar masses each) ~ 300 Mpc
 - BBH (30 solar masses each) ~ 700 Mpc
- 6 alerts were sent to EM partners with False alarm rate : 1/month



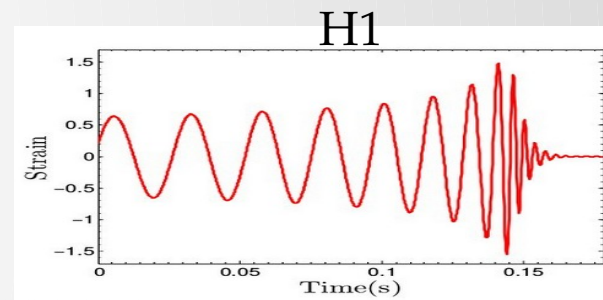
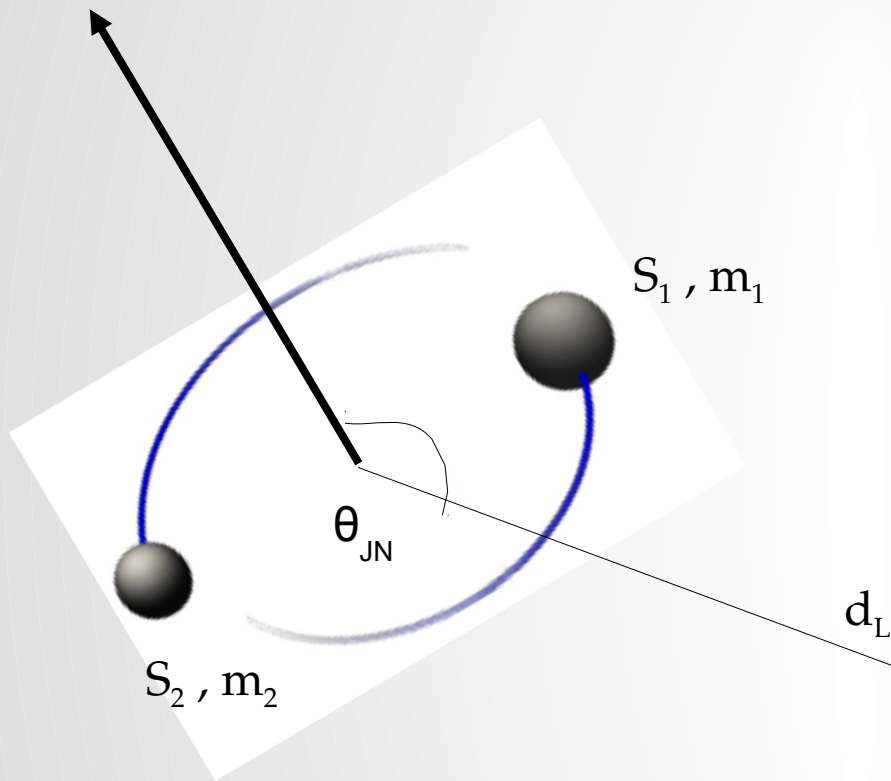


And one of them...

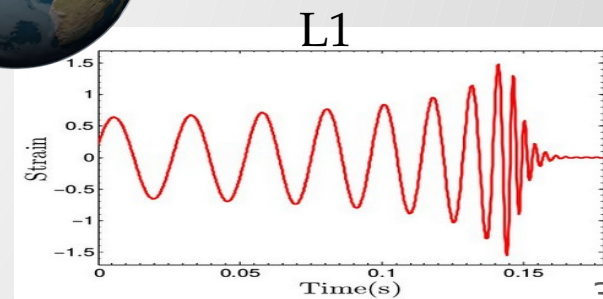
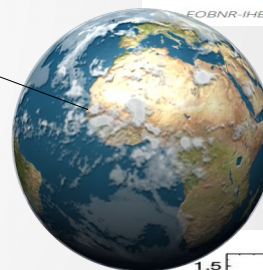
- Is a new detection : GW170104 !
- Announced yesterday at 5 PM CET
- Sky error region : 1200 sq. deg.



Parameters of the sources



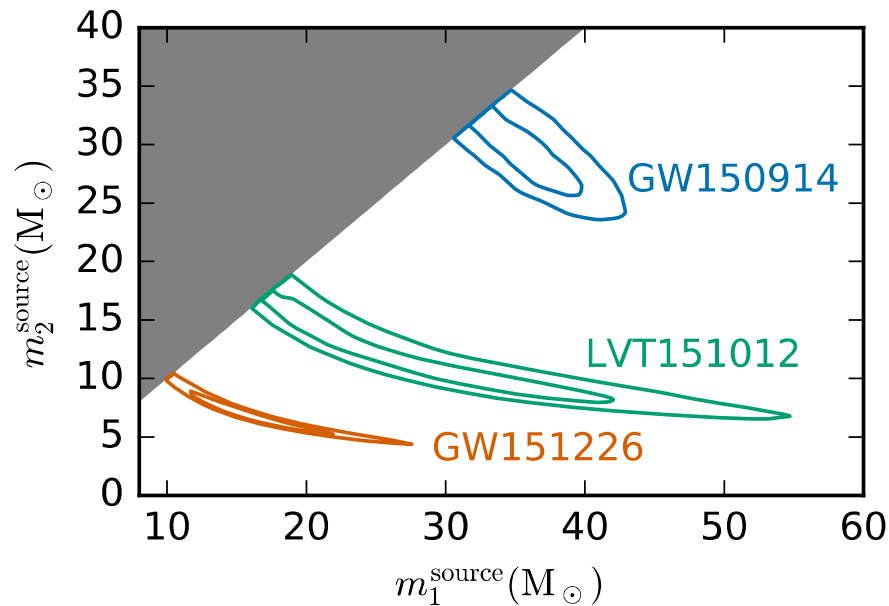
EOBNR-IHES waveform: $m_1=36M_{\text{sun}}$, $m_2=29M_{\text{sun}}$, nonspinning black holes



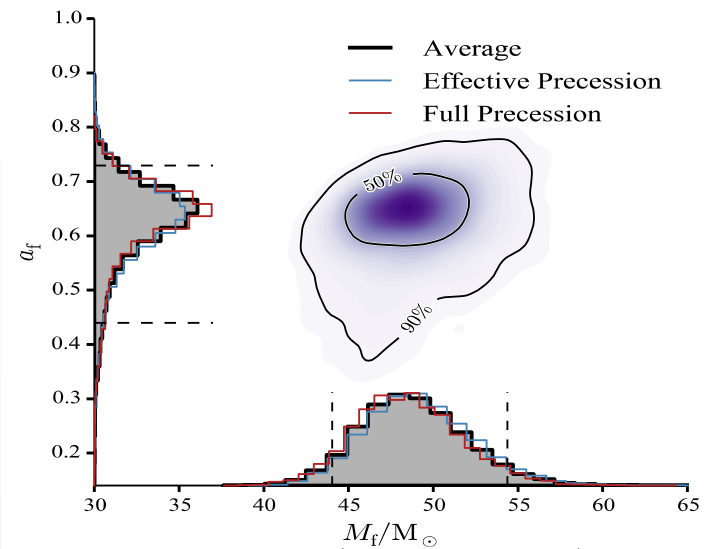
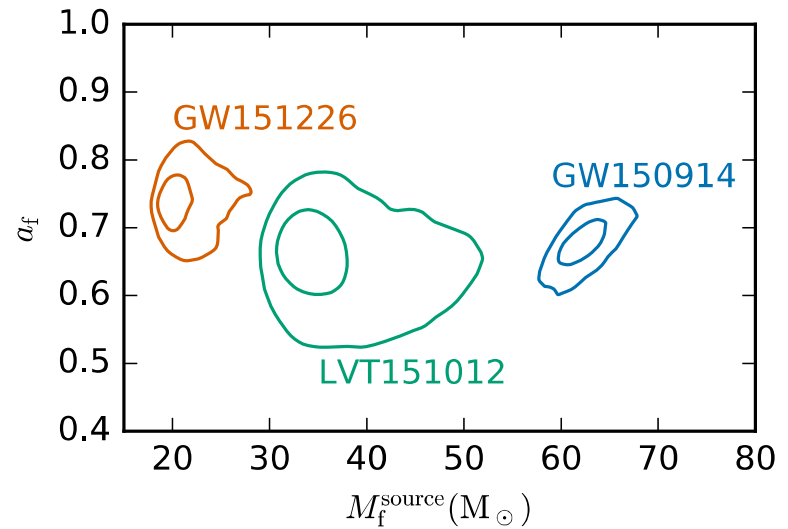
EOBNR-IHES waveform: $m_1=36M_{\text{sun}}$, $m_2=29M_{\text{sun}}$, nonspinning black holes

Parameters inference

Abbott et al, PRX 6 041015 (2016)



Initial masses

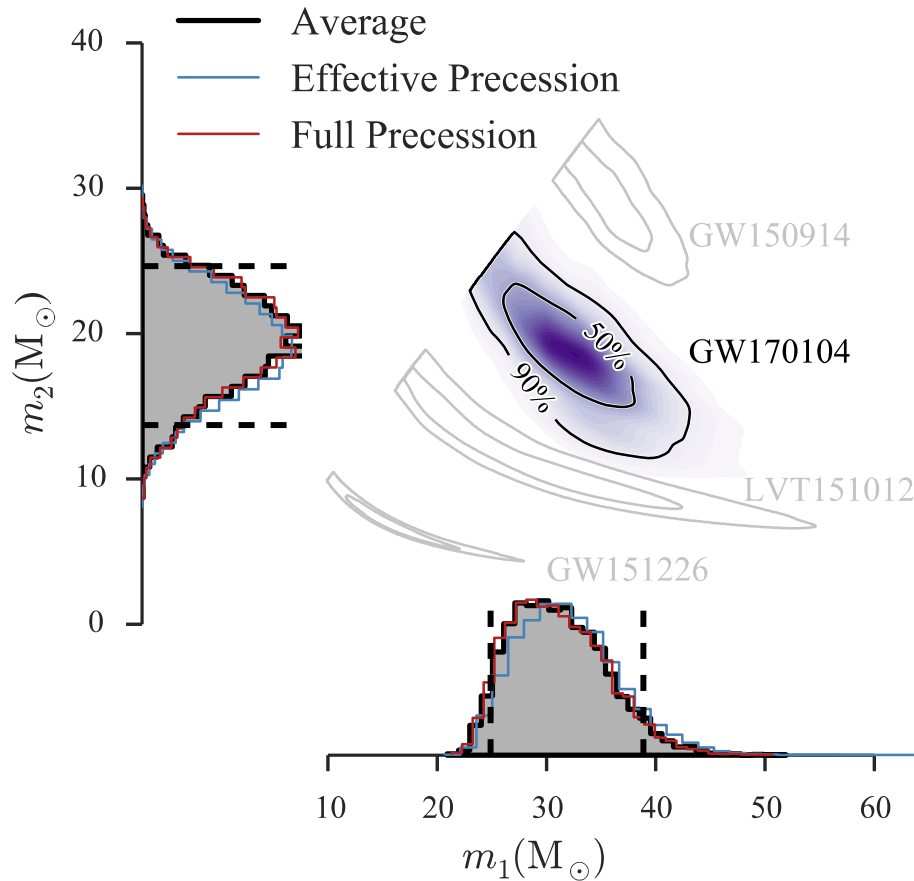


Final mass and spin

Abbott et al. PRL 118, 221101

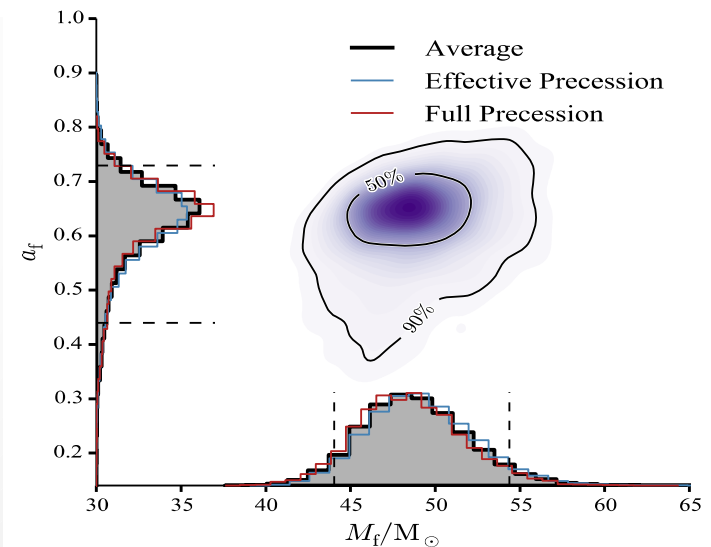
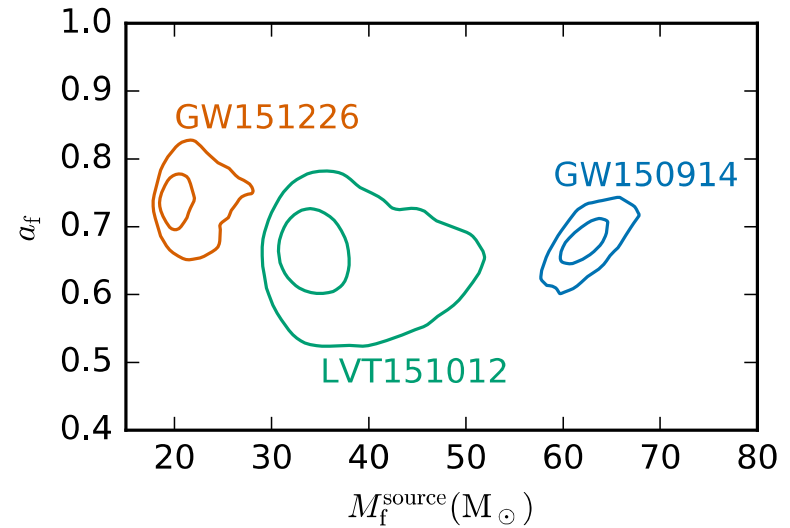
Parameters inference

Abbott *et al.* PRL 118, 221101



Initial masses

Abbott *et al.*, PRX 6 041015 (2016)

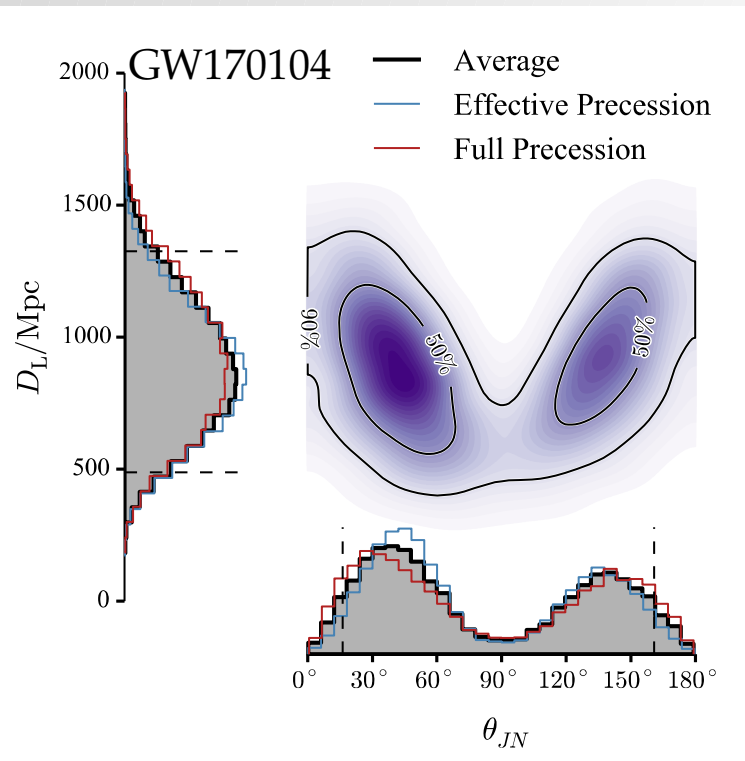


Final mass and spin

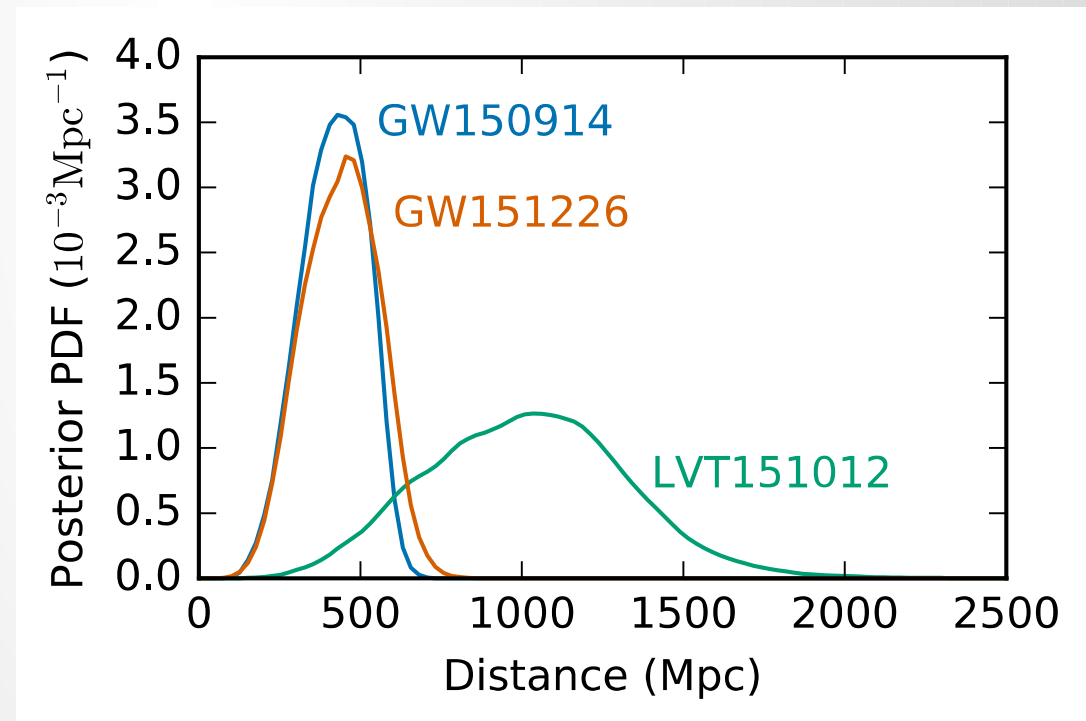
Abbott *et al.* PRL 118, 221101

Parameters inference

Abbott *et al.* PRL 118, 221101



Distance vs inclination angle have correlation



Abbott et al, PRX 6 041015 (2016)

Main parameters

Abbott et al, PRX 6 041015

Abbott *et al.* PRL 118, 221101

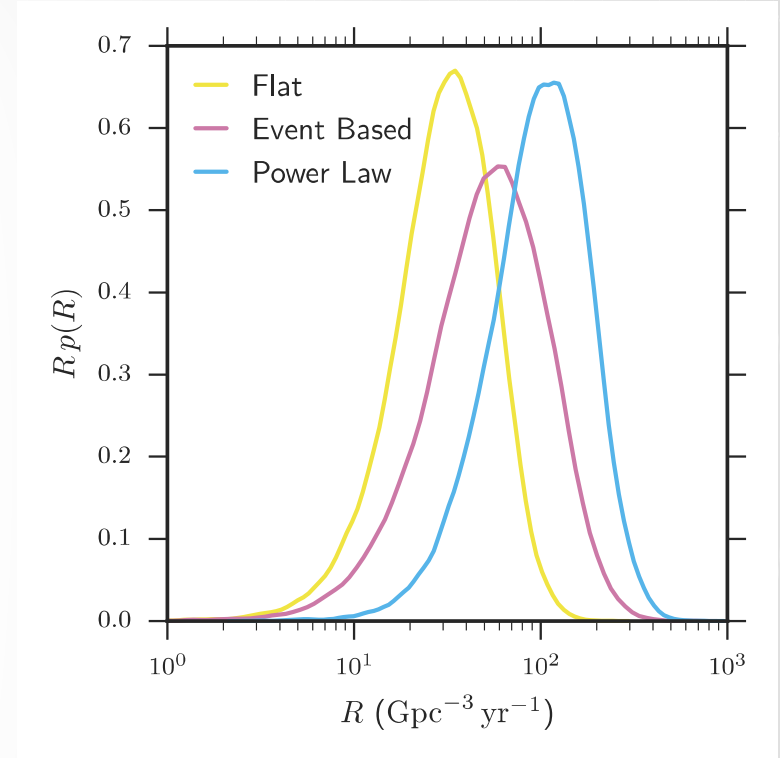
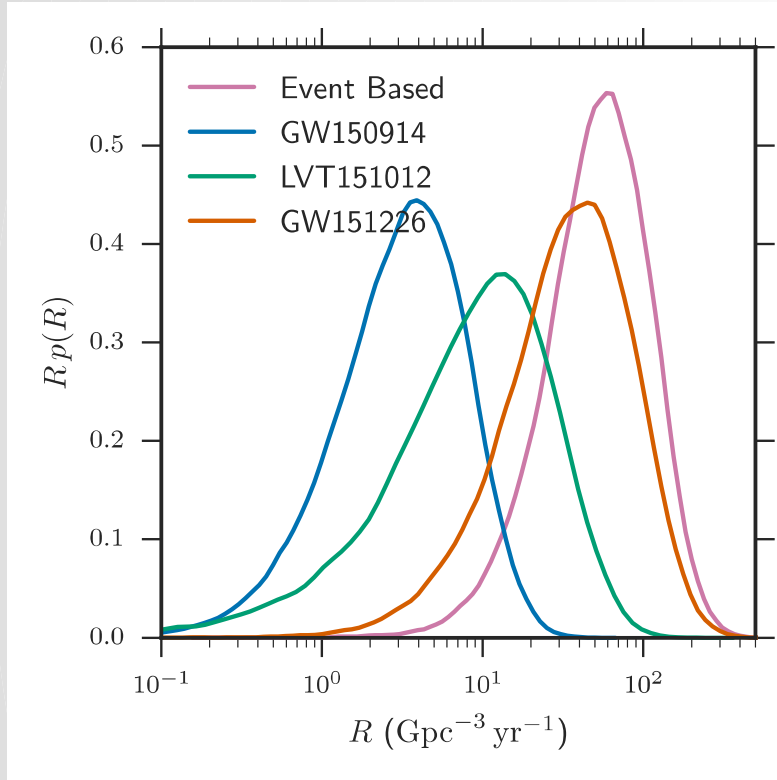
Event	GW150914	GW151226	GW170104
Primary mass $m_1^{\text{source}}/M_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary mass $m_2^{\text{source}}/M_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}^{\text{source}}/M_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass $M^{\text{source}}/M_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	$50.7^{+5.9}_{-5.0} M_\odot$
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$-0.12^{+0.21}_{-0.30}$
Final mass $M_f^{\text{source}}/M_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	$48.7^{+5.7}_{-4.6} M_\odot$
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.64^{+0.09}_{-0.20}$

Event	GW150914	GW151226	GW170104
Radiated energy $E_{\text{rad}}/(M_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\text{peak}}/(\text{erg s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.7}_{-1.3} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	880^{+450}_{-390}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.18^{+0.08}_{-0.07}$

- GW150914 is compatible with a coalescence of 2 black holes with similar mass, more asymmetries for the others
- GW150914 : $3 M_\odot$ in energy were radiated through GW emission – highest luminosity ever observed
- Final object is compatible with a Kerr black hole

BBH merger rate

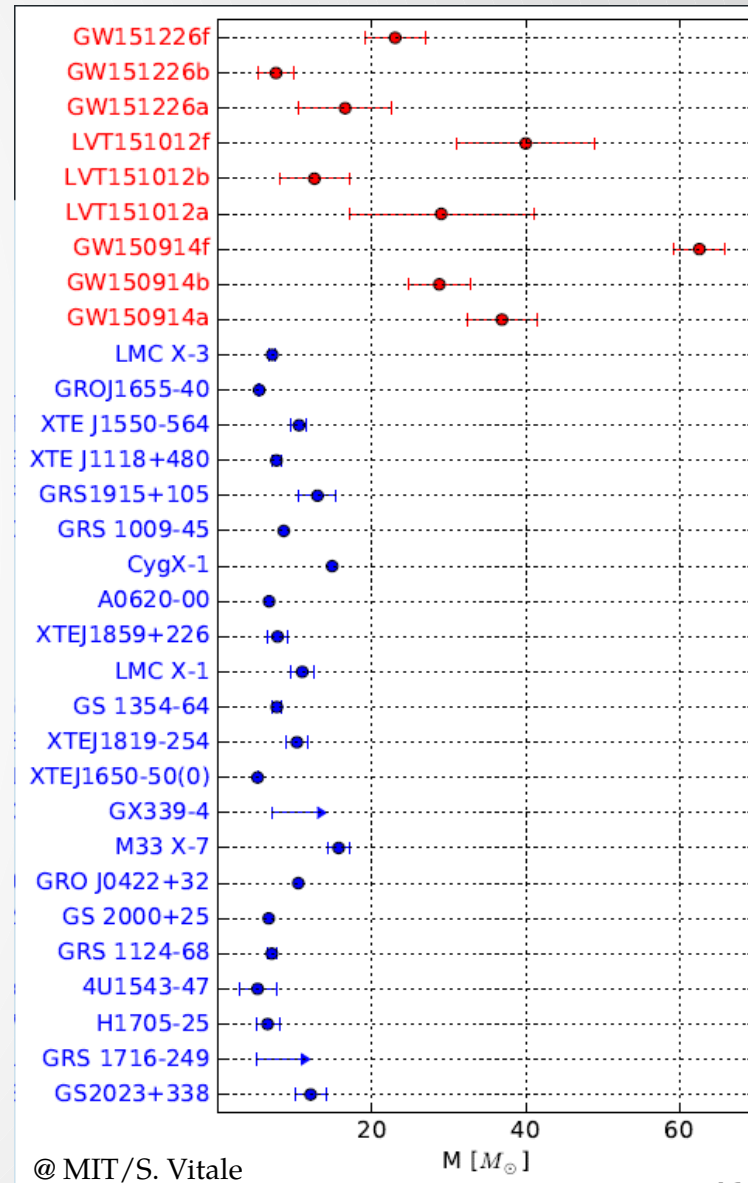
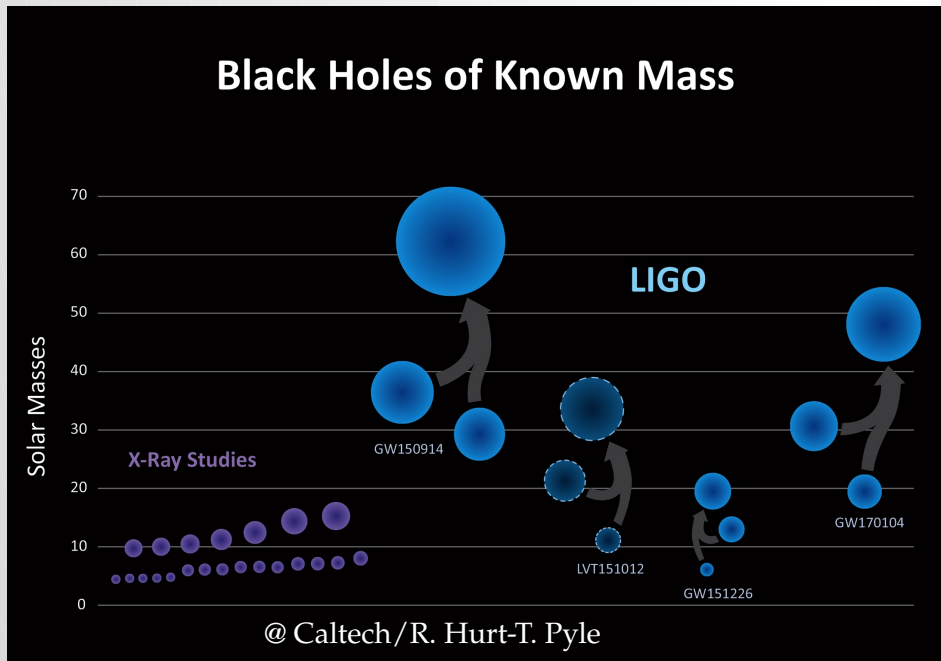
Abbott et al, PRX 6 041015 (2016)



- Assuming constant volume up to horizon ($z \sim 0.5$)
- Different distributions
- Using all infos $R = 12 - 213 \text{ Gpc}^{-3} \text{yr}^{-1}$ (including GW170104)

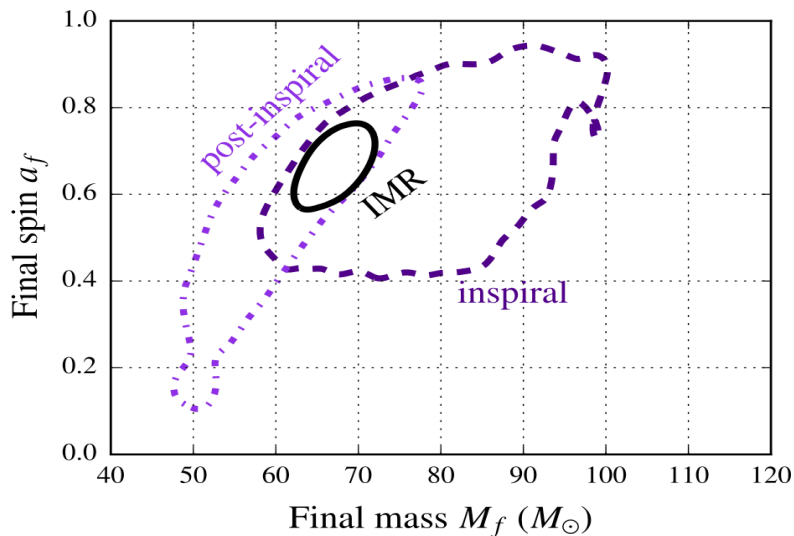
Black hole population ?

- Events observed are much heavier than what has been observed in X-ray 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

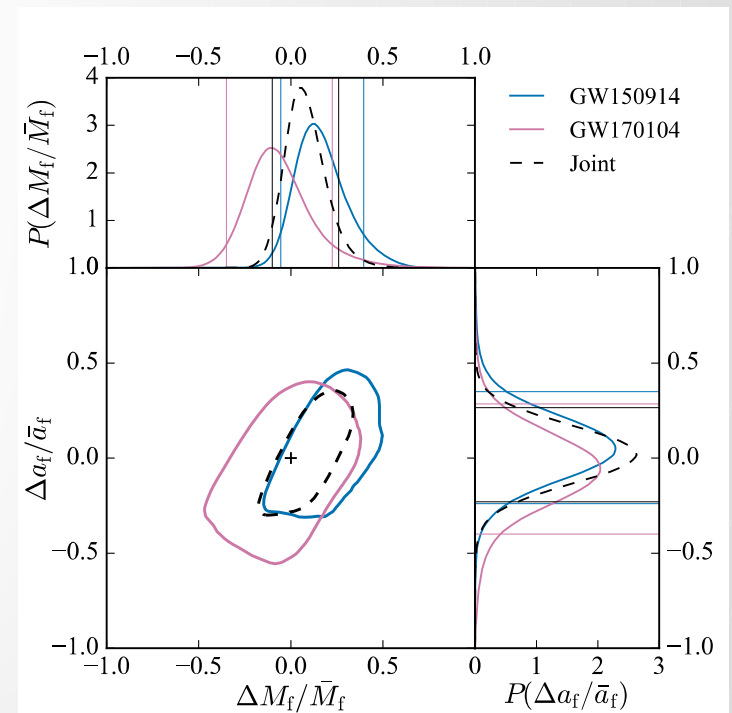


Testing General relativity in a new regime

- We have for the first time test under highly relativistic and non linear conditions
- Different tests can be performed :
 - 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 the remaining time serie



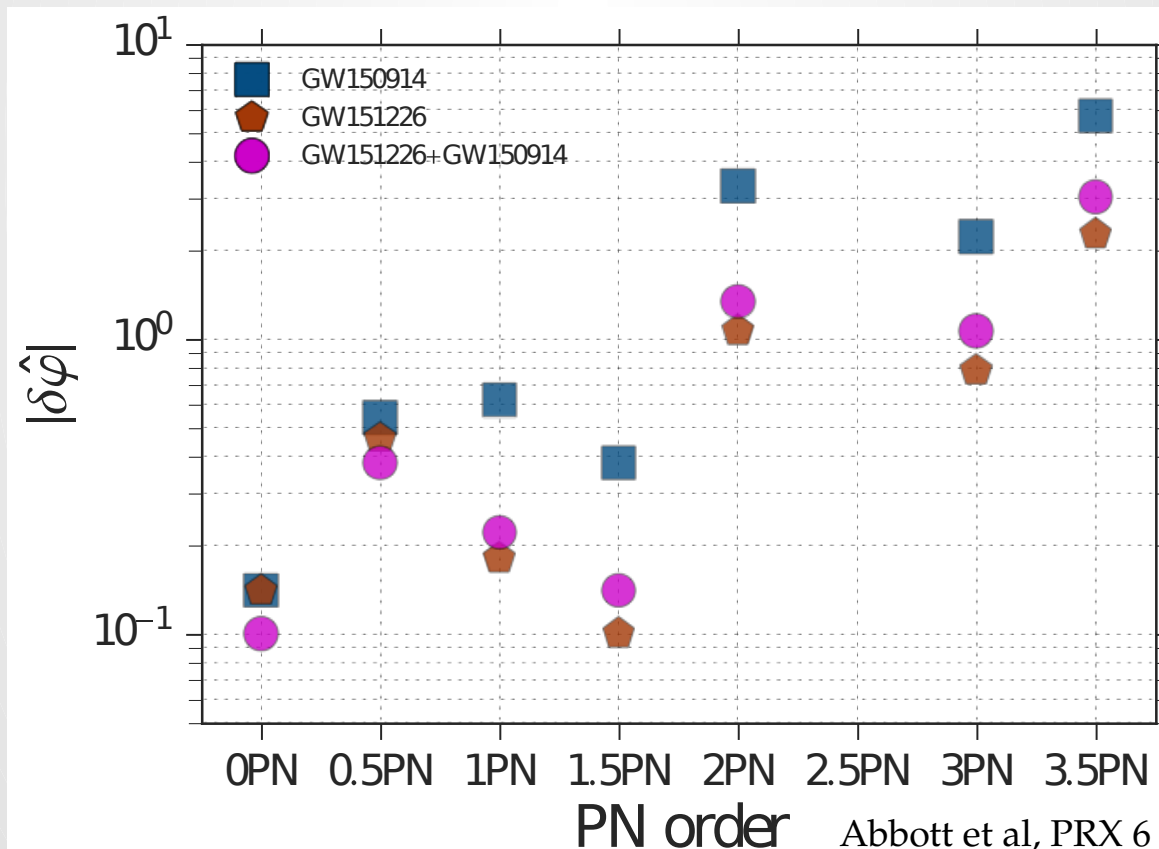
Abbott *et al.* PRL 116, 221101



Abbott *et al.* PRL 118, 221101

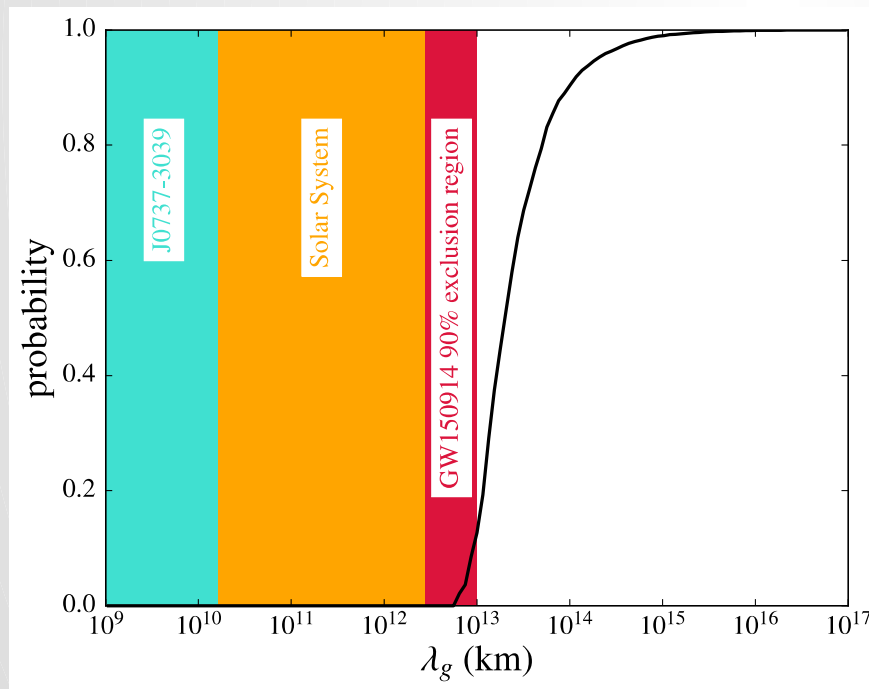
Constraining parametrization deviations

- 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



Can we say something on graviton ?

- If we postulate a massive graviton we need to take into account Yukawa type correction to Newtonian potential
- This will induce a dispersion depending of the frequency and can tested with 1 PN order



$$\frac{v_g^2}{c^2} = 1 - \frac{h^2 c^2}{\lambda_g^2 E^2}$$

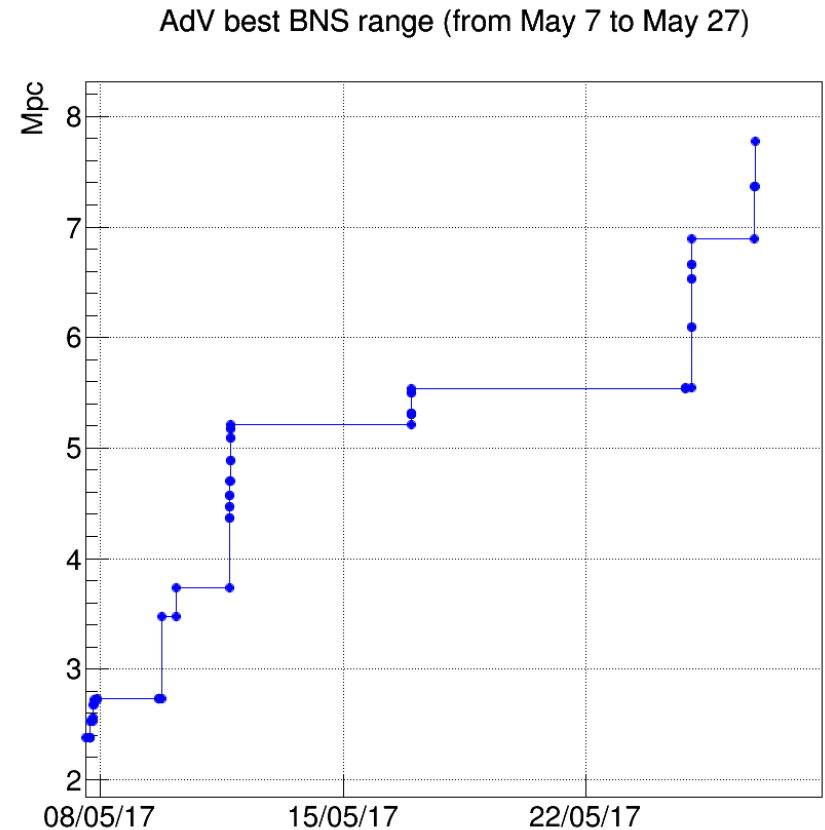
$$\lambda_g = \frac{h}{m_g c}$$

$$\lambda_g > 10^{13} \text{ km}$$

$$m_g < 10^{-22} \text{ eV}$$

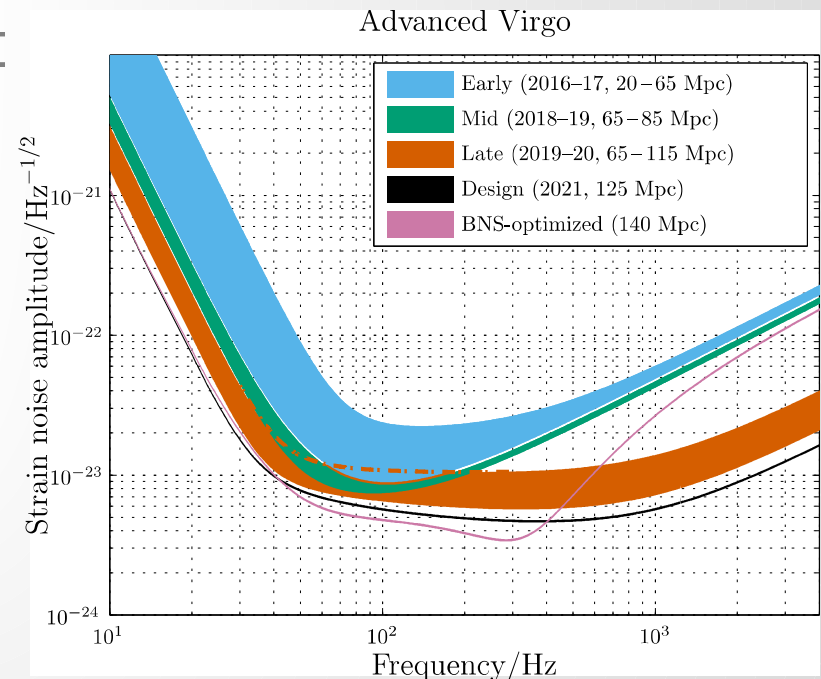
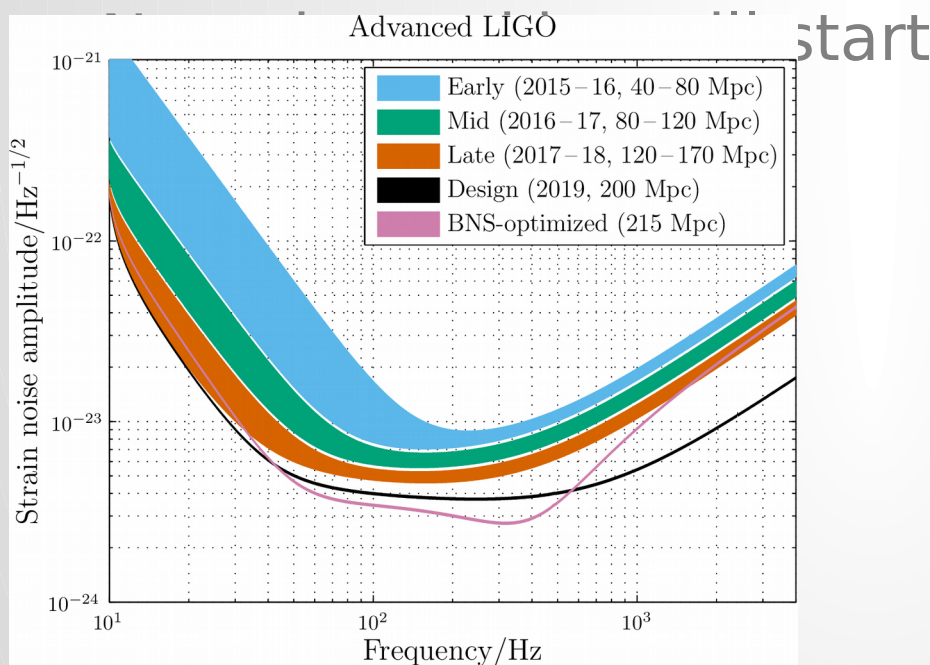
Some news from Virgo

- Installation process take more time than expected
 - Need to modify part of the suspensions due to aging of some components
 - Problem with monolithic suspensions (related to vacuum system)
- Lock acquired in few months
- Advanced Virgo operating with stable lock on dark fringe
- >85% duty cycle in recent commissioning run
- Sensitivity steadily improving
- Plan to join O2 in the next weeks (BNS > 15 Mpc)



LIGO and Virgo in the next years

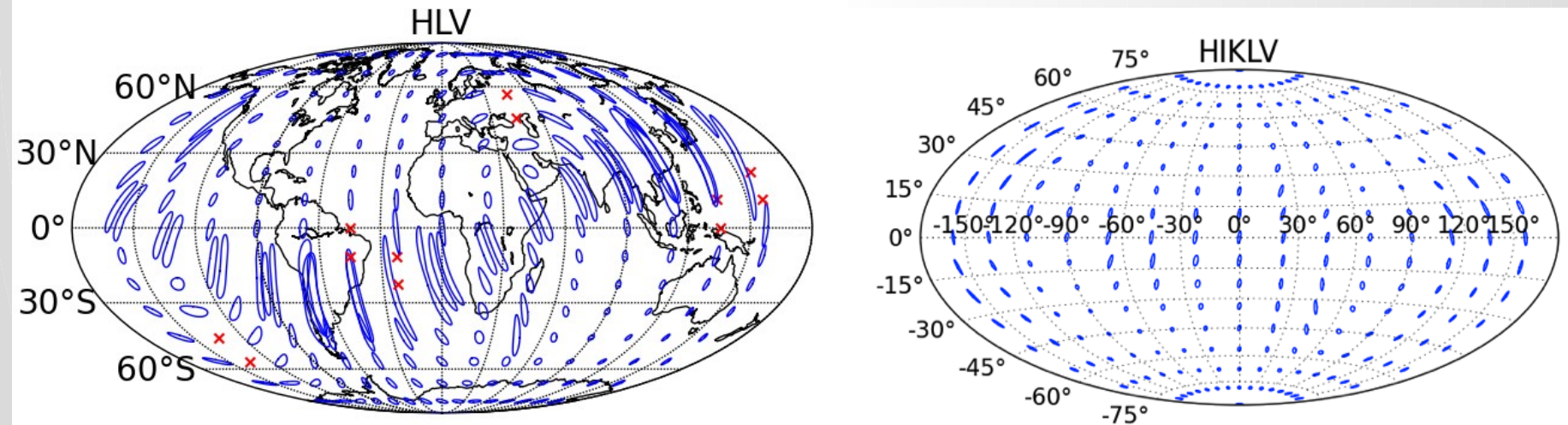
- Third detector :
 - May increase number of sources (more up time with at least two detectors)
 - Improve sky localization if seen by the three : from x00 sq deg. to x0 sq deg.
 - One more measure is more constraints
- Upgrade plans on LIGO and Virgo interferometers



New detectors not far away

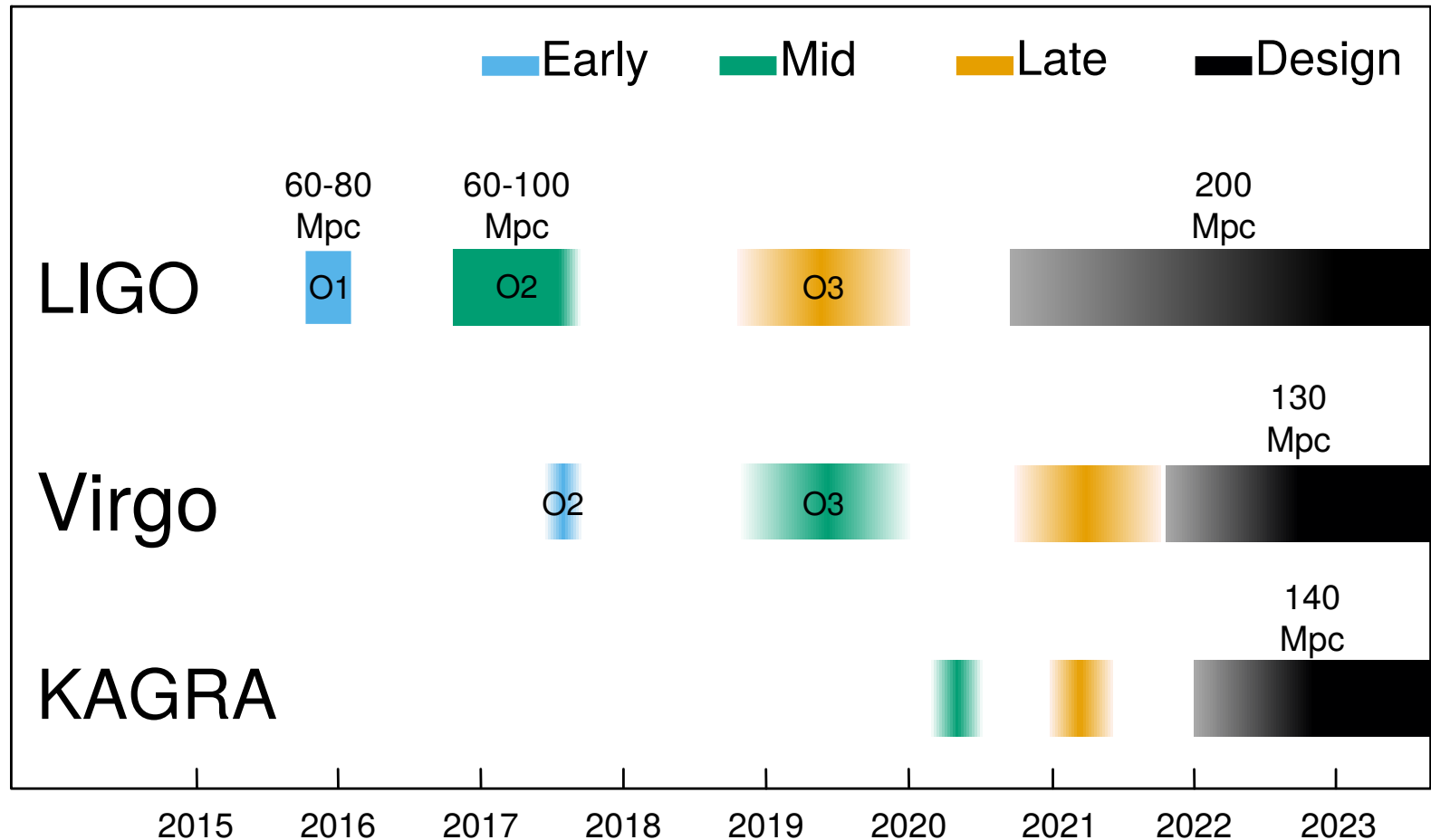
- KAGRA is well advanced – we may have comparable sensitivity before 2020 (?) – new technologies will also be tested
- India recently accepted to host a LIGO interferometer, we may have a 5th detector in 2020-2022

Fairhurst, proceedings of ICGC2011 conference



Comparison between 3 and 5 detectors for sky localization

Observing scenario



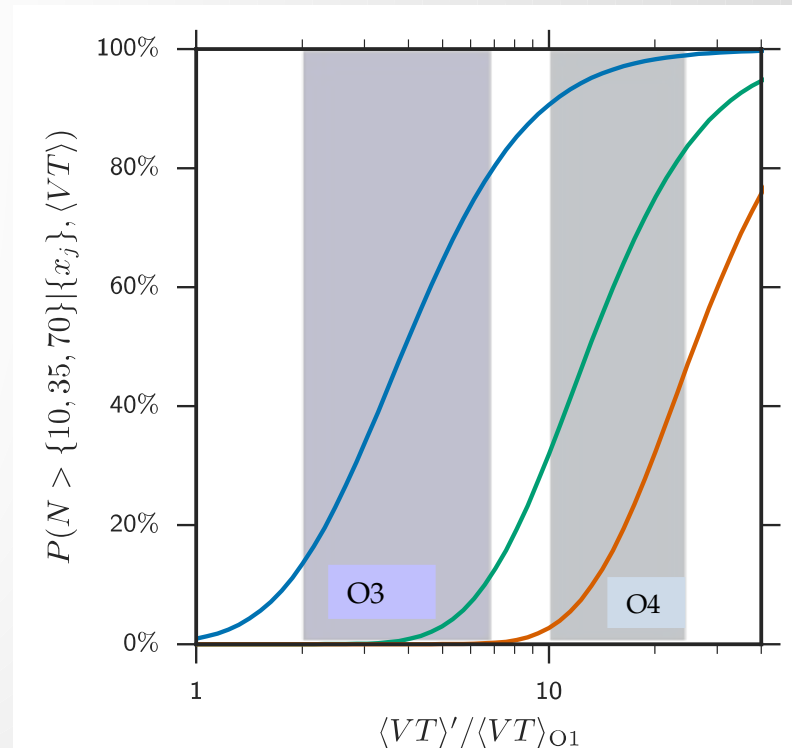
At the end

- We have made the first direct detections of an astrophysical event with gravitational wave
- We have for the first time observed two binary black hole systems and their mergers
- We have observed several high mass binary systems

We are opening new ways to observe the Universe and its densest parts

We will also be able to test GR in new regimes

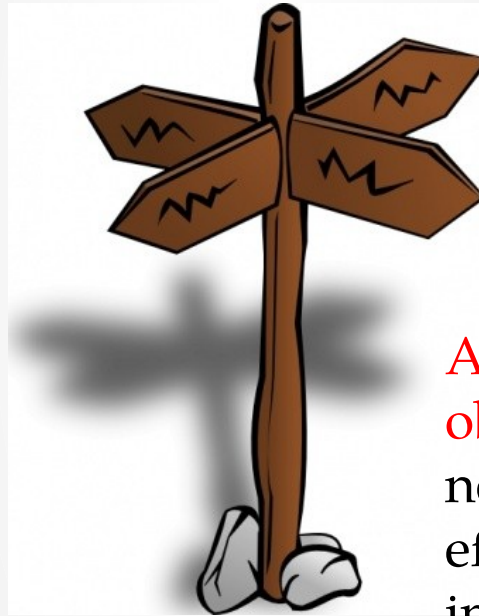
Time around 2020 will be very interesting for transient sky (including LSST) and tests for gravitation !



GW : a crossroad of science frontiers

General relativity: relativistic & compact objects (strong field relativity tests).

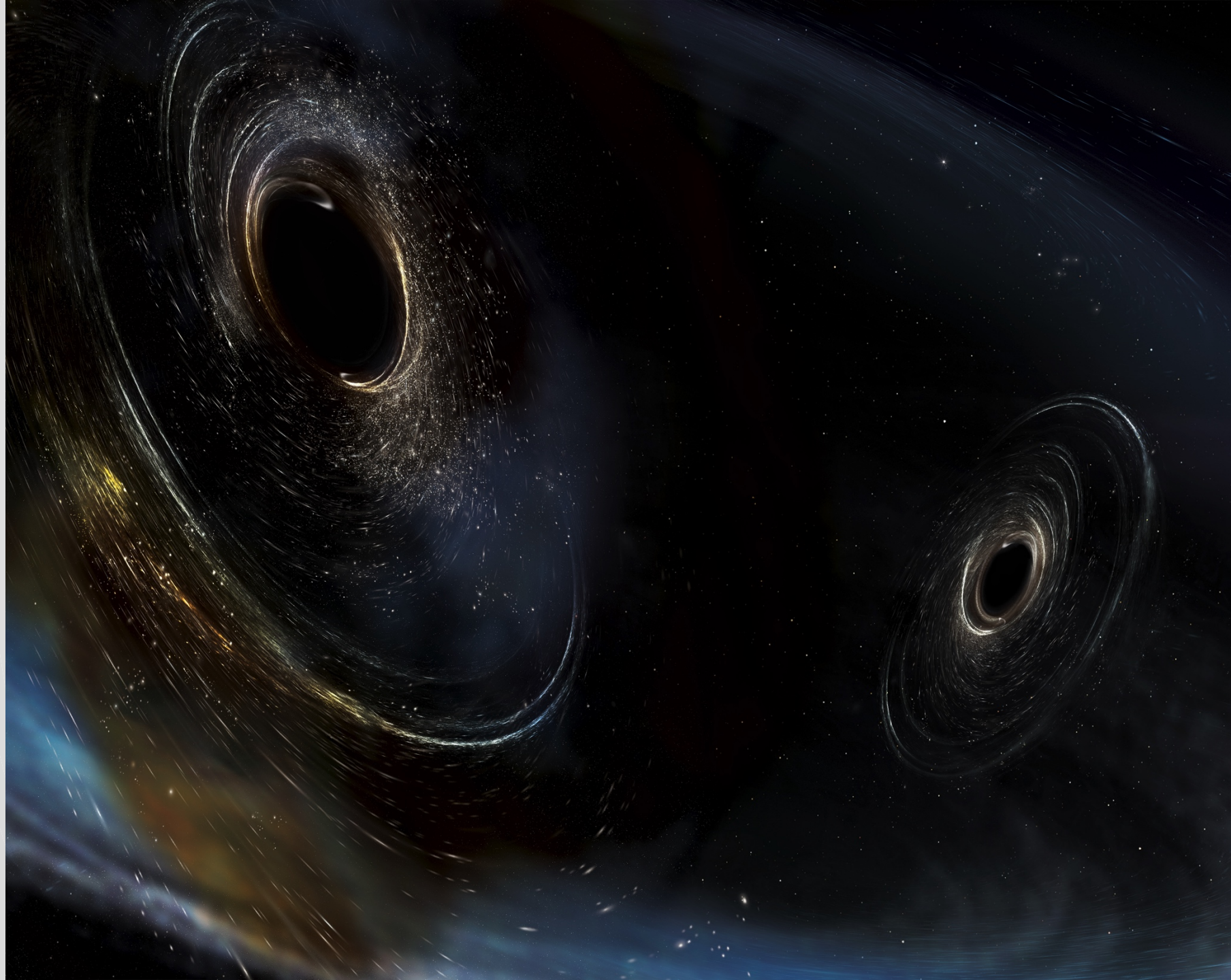
Laser interferometry detectors: first generation of detectors has proven technology works. Second generation should be more sensitive by 1 order of magnitude.



Cosmology: reach cosmological distances for black hole GW sources.

Astrophysics of compact objects: black holes & neutron stars with matter effects. Most energetic objects in the Universe.

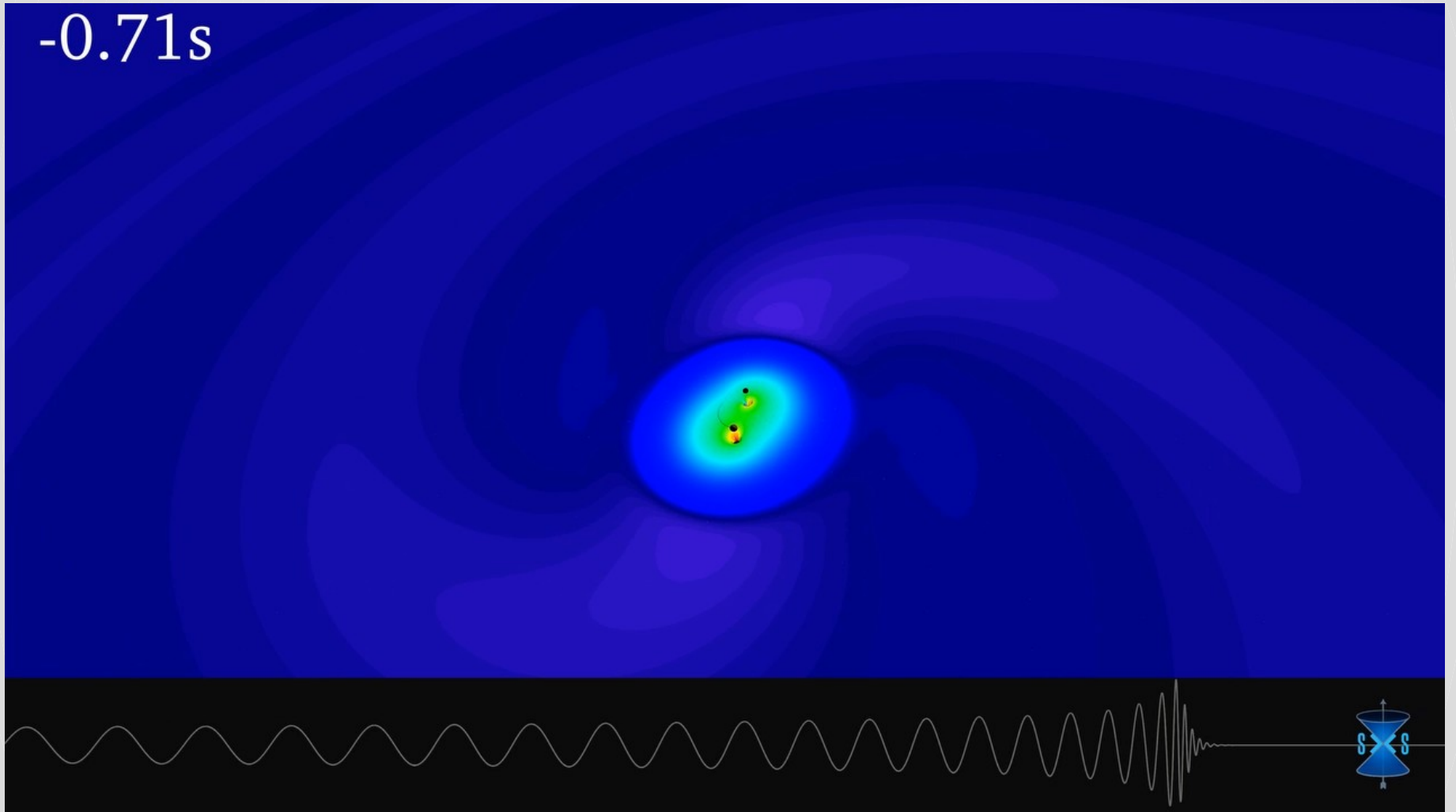
Data analysis: how to extract low signal-to-noise ratio signals in high dimensional parameter space & in non-Gaussian/non-stationary data environment.

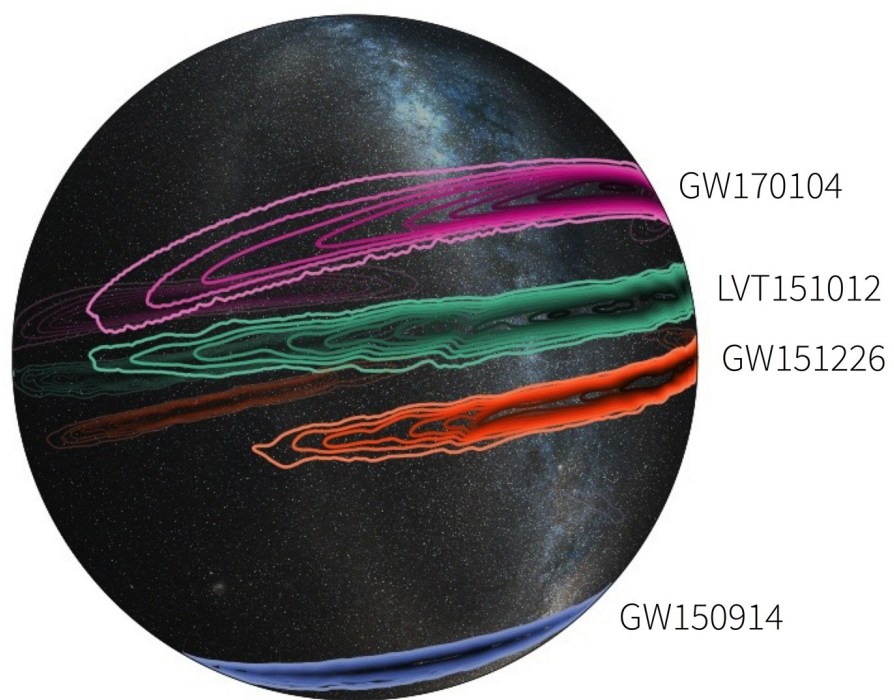
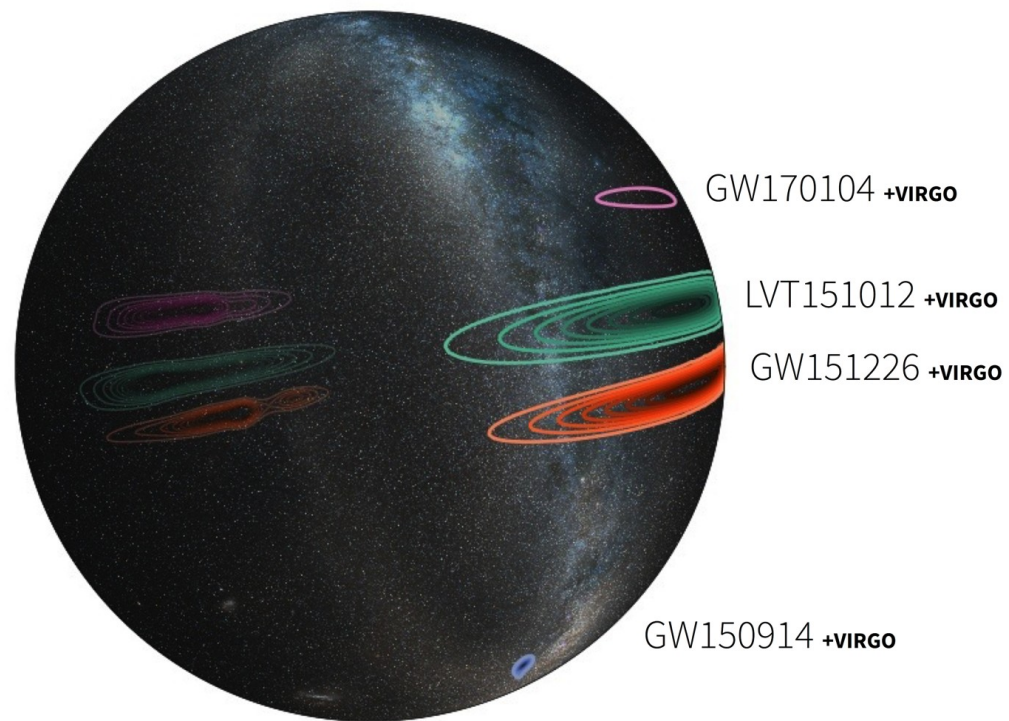


backup

...

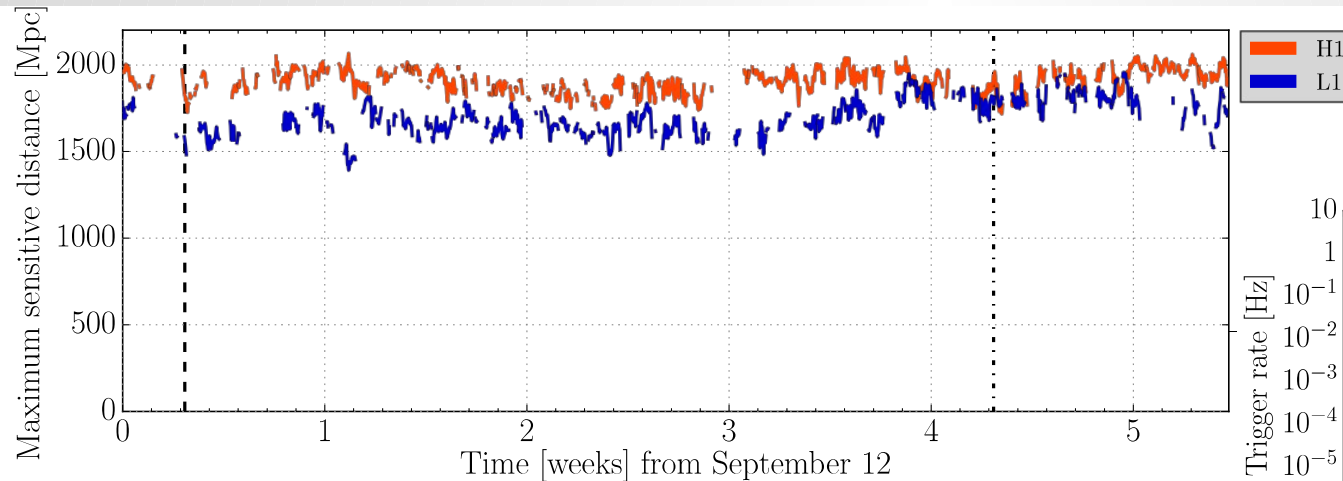
-0.71s



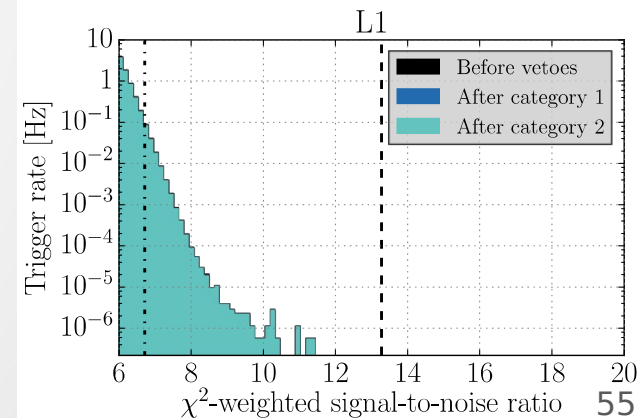
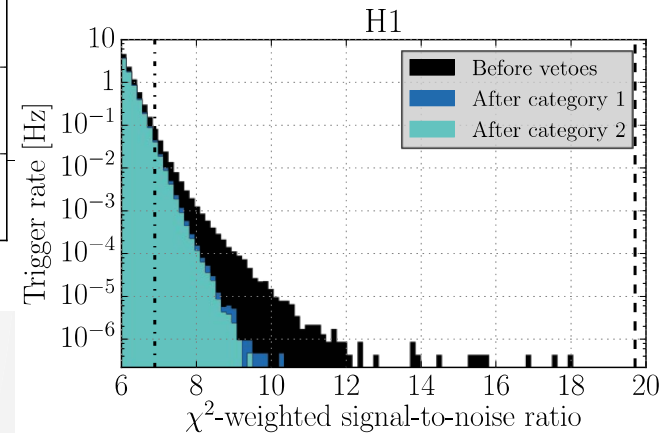


Checks on data quality

- Stability for the whole period used for background estimations : OK



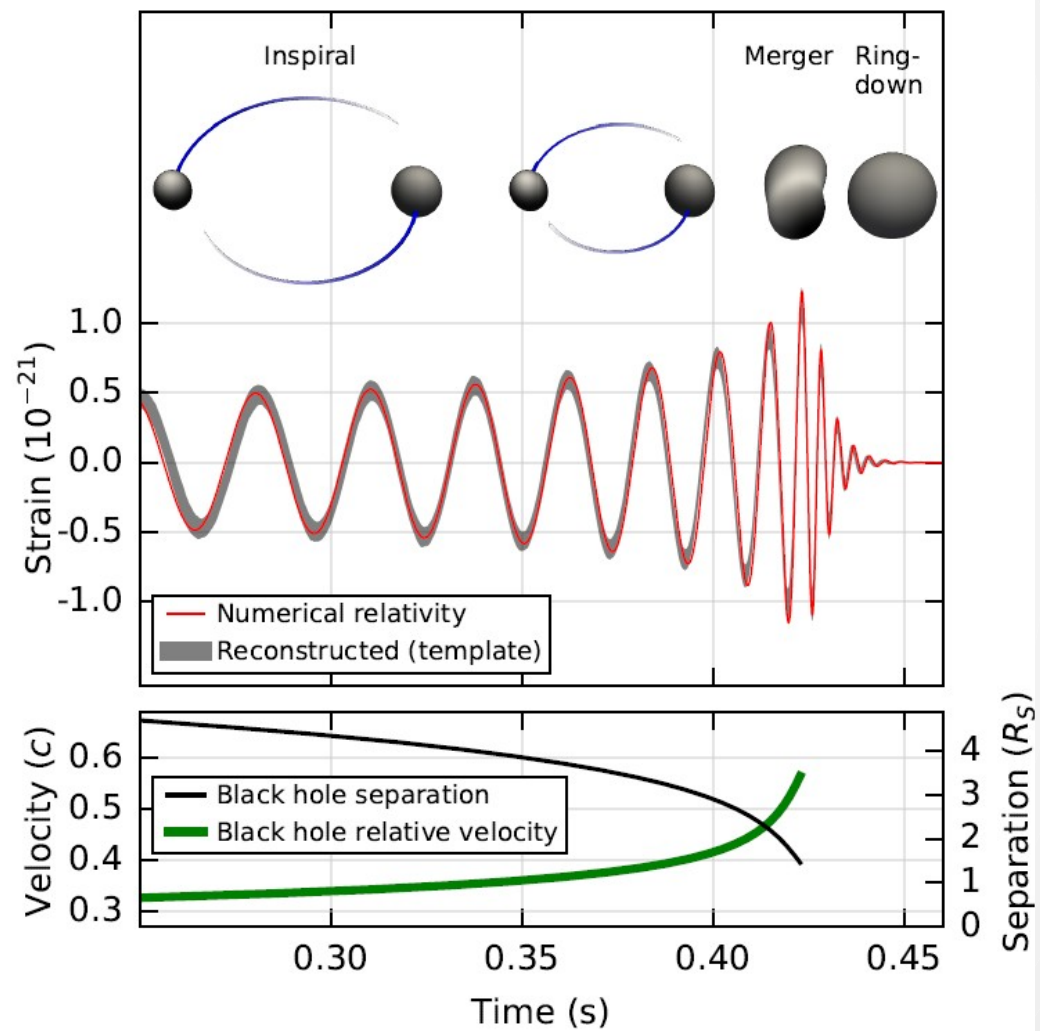
- Periods removed
H1 $\sim 5\%$ - L1 $\sim 0.1\%$



In terms of rates for BNS

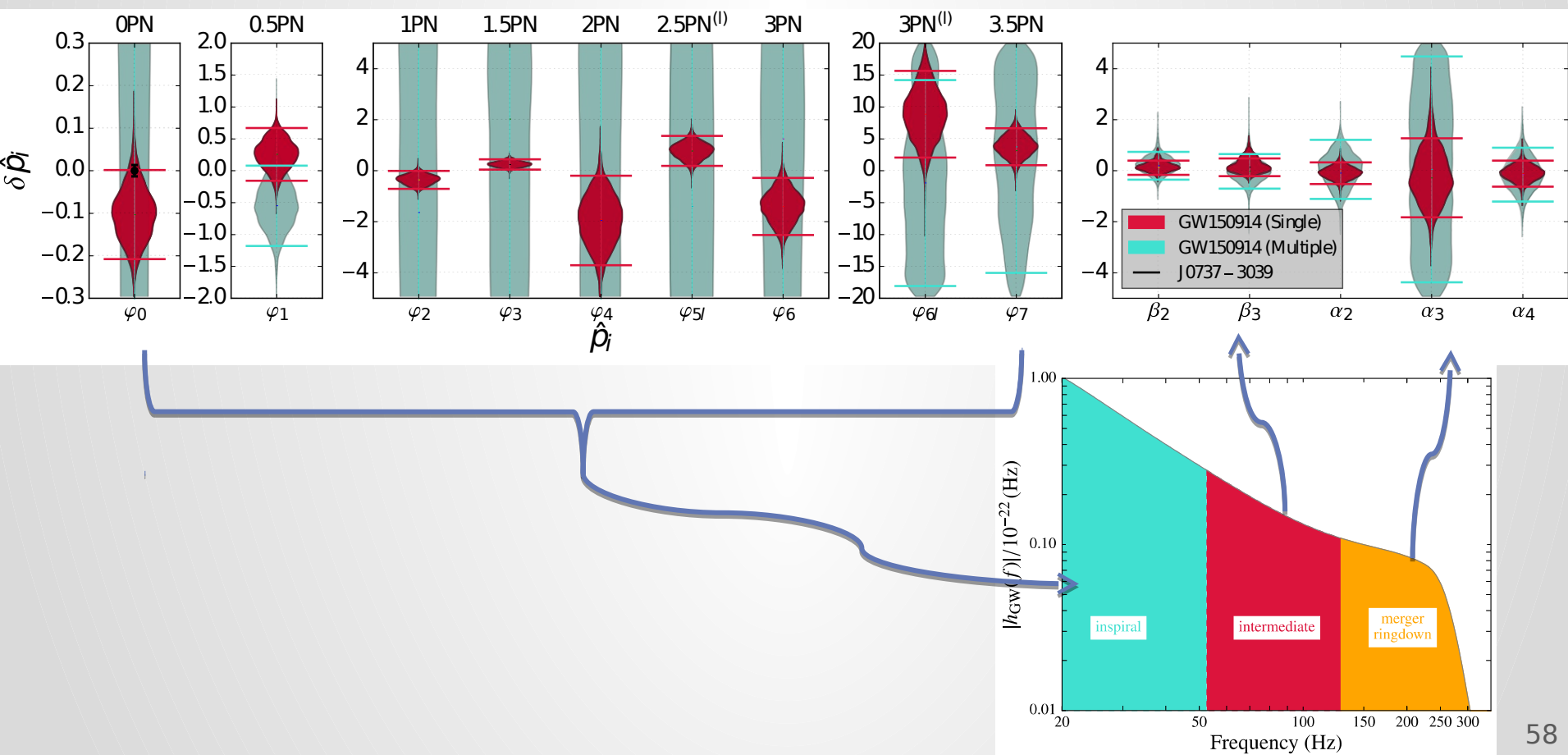
Epoch	Estimated Run Duration	Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg ²	20 deg ²
2015	3 months	40 – 60	—	40 – 80	—	0.0004 - 3	-	-
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 - 20	2	5-12
2017–18	9 months	75 – 90	40 – 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

Abbott et al, Living Reviews in Relativity 19, 1



Constraining parametrization deviations

- Constraints depend of the evolution
- Can be done either allowing **all parameters** to fluctuate or a **single one**



Go further and more compact

Source : mass M , size R , period T , asymmetry a $\blacktriangle$ $\ddot{Q} \approx a M R^2 / T^3$

Quadrupole formula becomes : $P \approx \frac{G}{c^5} a^2 \frac{M^2 R^4}{T^6}$

New parameters

- characteristic speed v
- Schwarzschild Radius $R_s = 2GM/c^2$

$$P \approx \frac{c^5}{G} a^2 \left(\frac{R_s}{R} \right)^2 \left(\frac{v}{c} \right)^6$$

Needs to have

- Compact object : $R \sim R_s$
- Relativist : $v \sim c$
- asymmetric



Neutron star (NS)
Black hole (BH)