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



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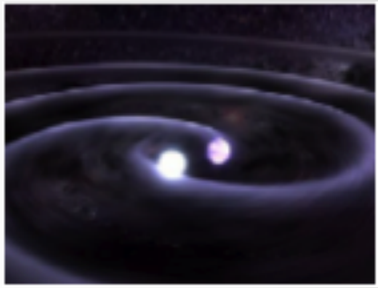
LIGO

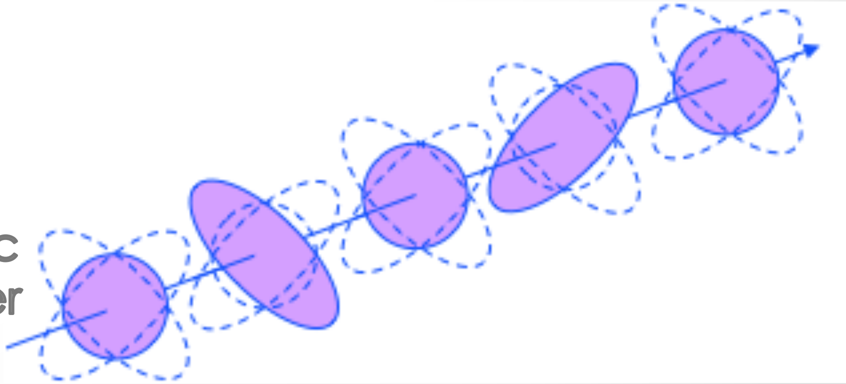
LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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 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*** $\Rightarrow$ $\dddot{Q} \approx a\,M\,R^2\,/\,T^3$

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

« G/c⁵ very small , c⁵/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

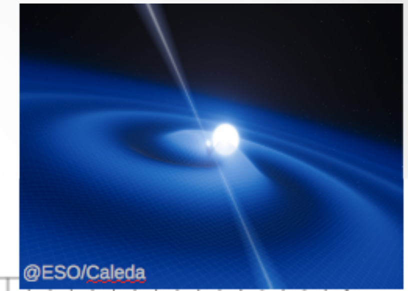
- Compact object : R~Rs
- Relativist : v ~ c
- asymmetric

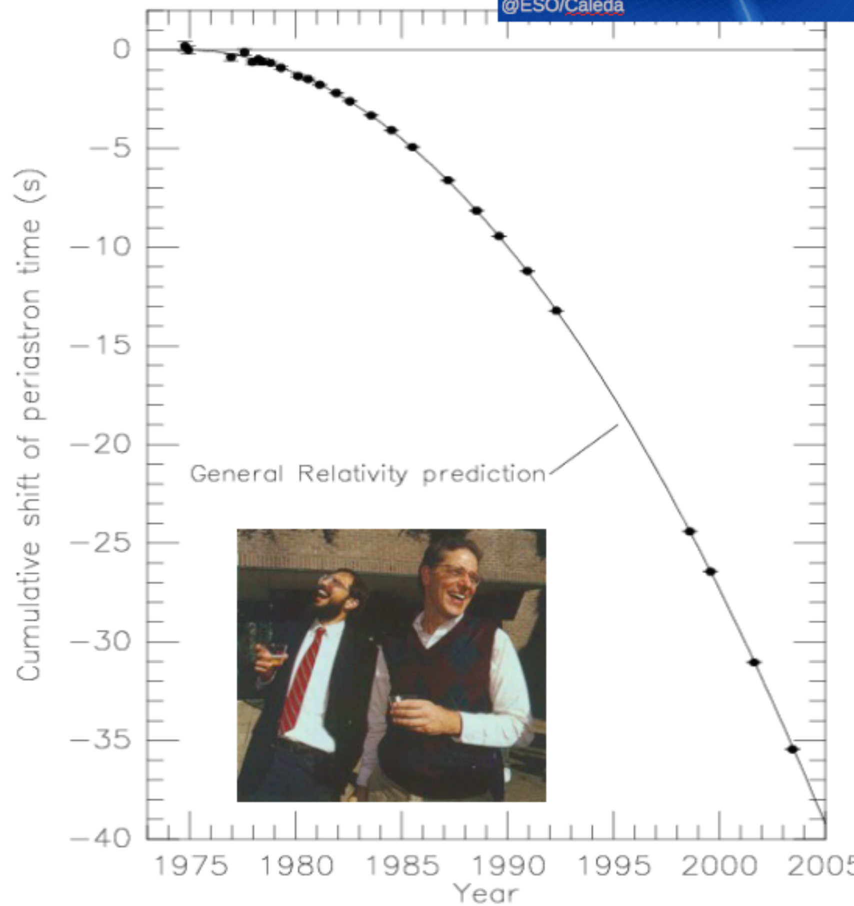
Neutron star (NS)
Black hole (BH)

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.)

1960's: first Weber bars

1963: rotating BH solution (Kerr)

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)

End of 1980's: Virgo and LIGO proposals

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

1990's: LIGO and Virgo funded

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

2005-2011: initial IFO « science » » runs

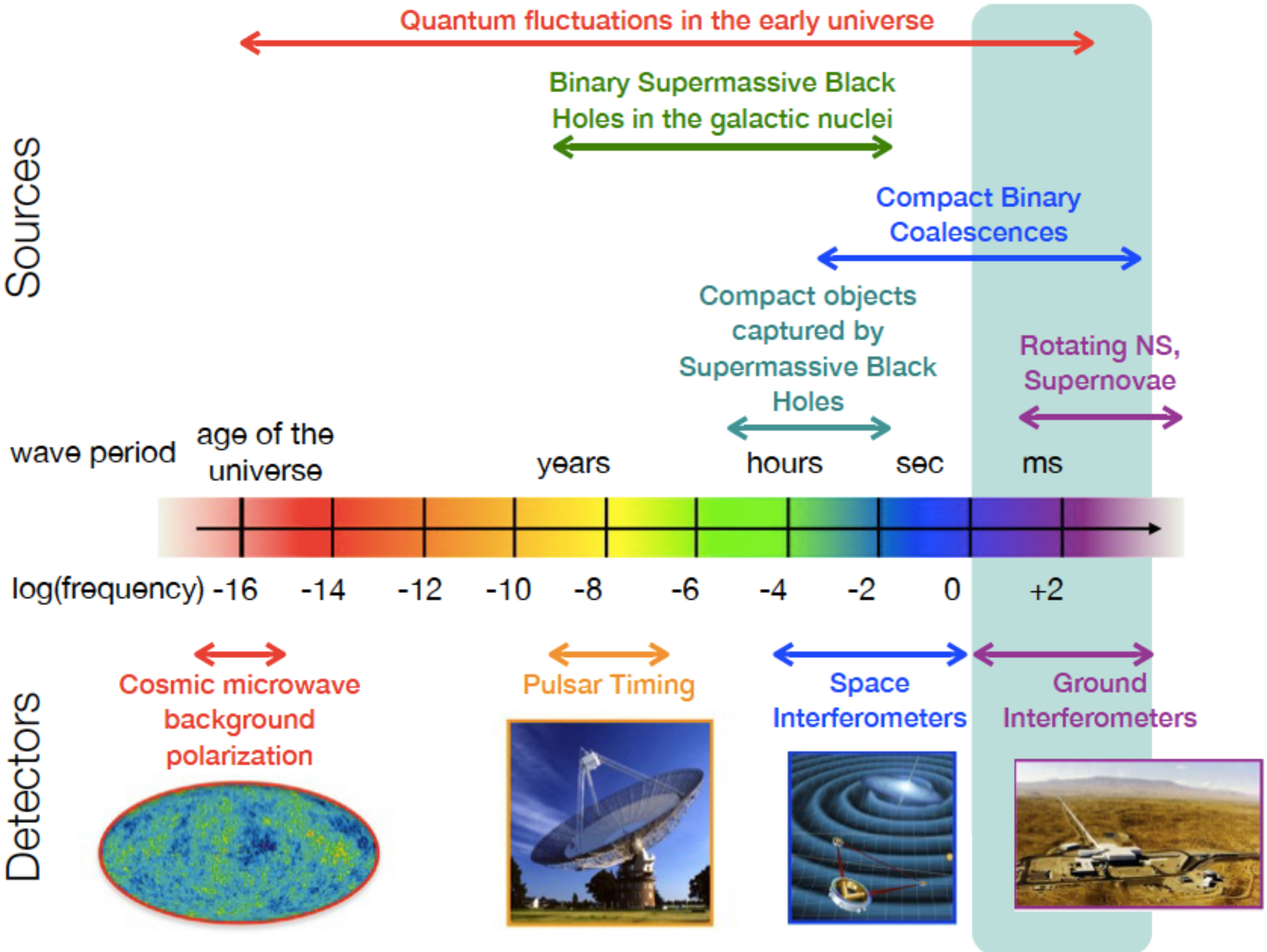
2006: BBH merger simulation (Baker, Lousto, Pretorius, etc.)

2007: LIGO-Virgo Memorandum Of Understanding

2012 : Advanced detectors funded

2015: First Advanced LIGO science run

The Gravitational Wave Spectrum

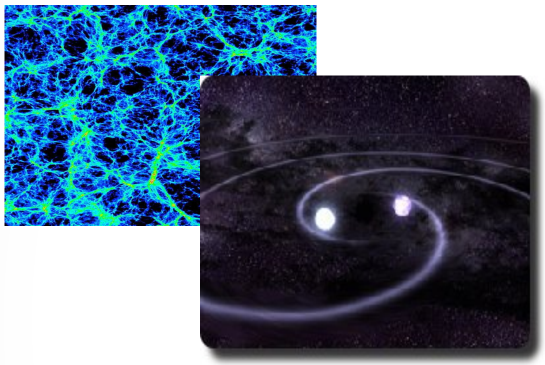


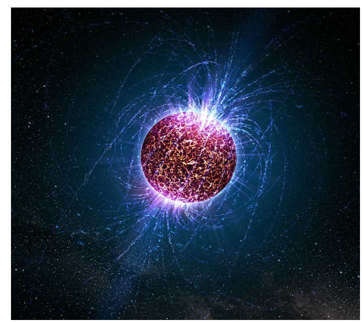
[Inspired from http://science.gsfc.nasa.gov/663/research/]

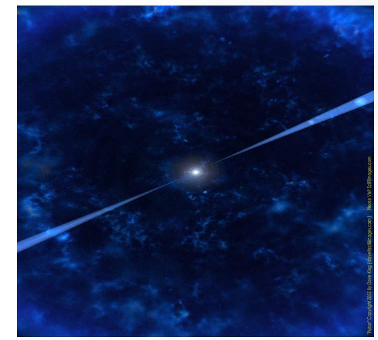
GW zoology

Short duration (1sec) Long duration (∞)

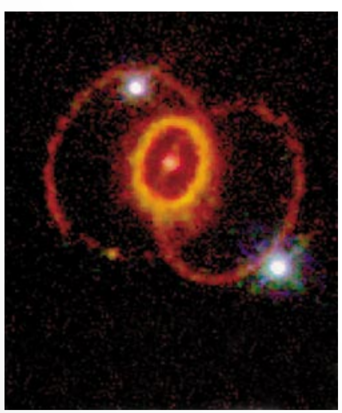
Waveform known



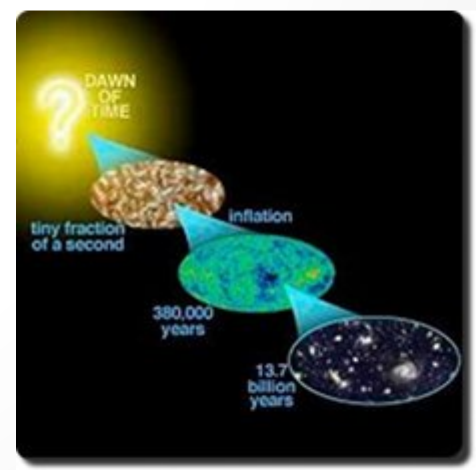




Waveform unknown



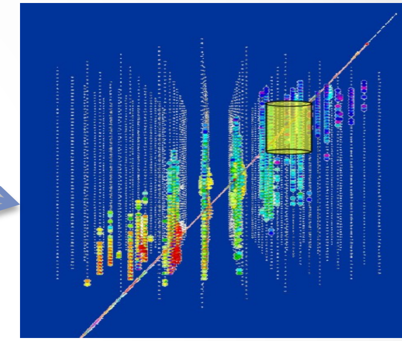
?



Multimessenger astronomy

Gamma-rays

HE (>1 TeV) ν

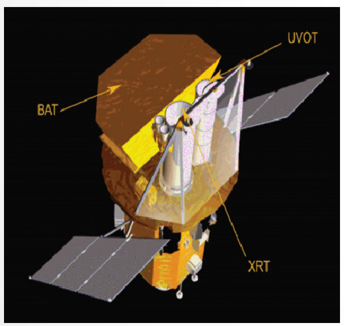


GRB

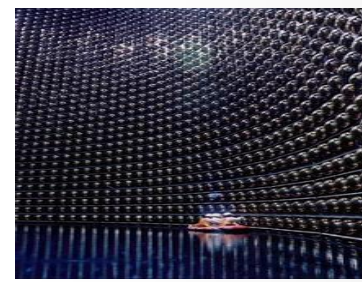
SGR/AXP

Supernovae
type II

X-rays



LE (MeV) ν



Giant Flare

Pulsar/
pulsar glitches

Optical

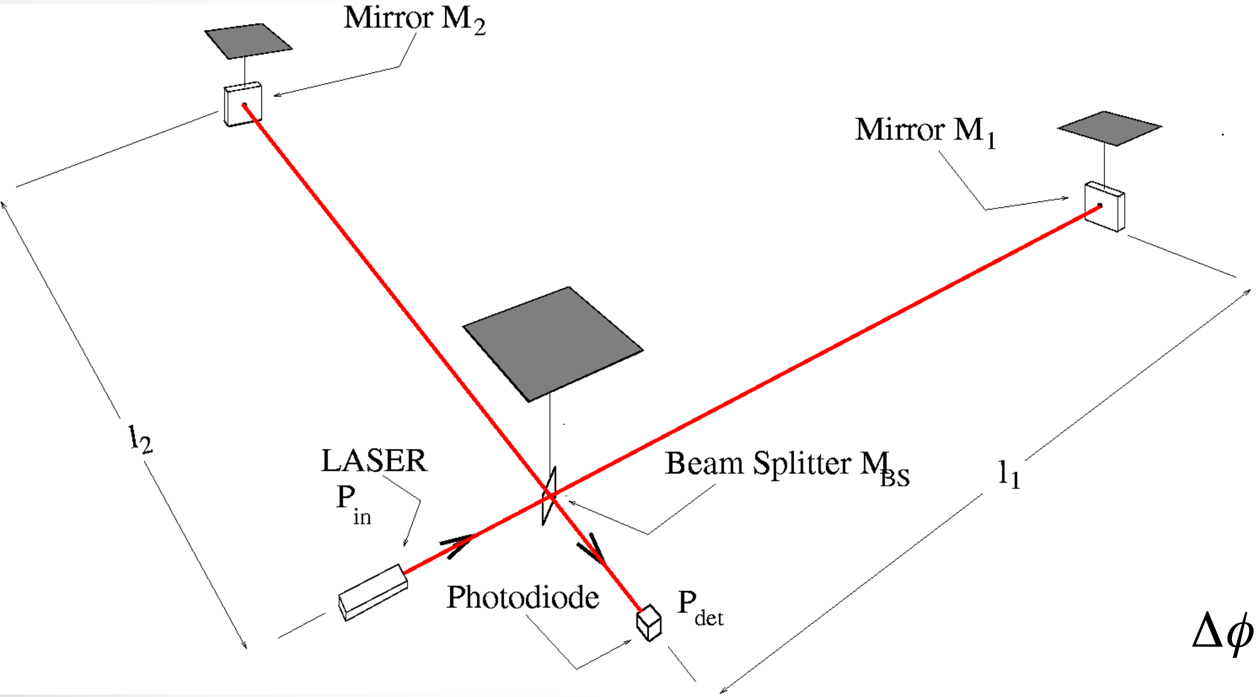
Radio

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 (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, primodial universe
- …..

Suspended interferometer

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



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

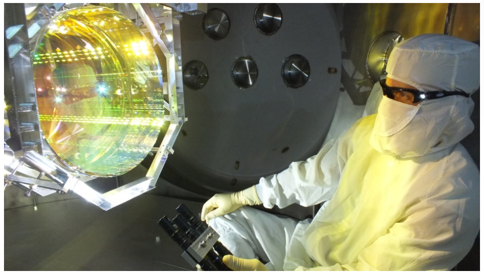
$$C = \frac{2r_1r_2}{r_1^2 + r_2^2}$$

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

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

Advanced generation !

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

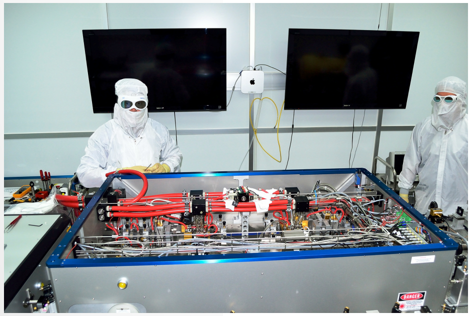


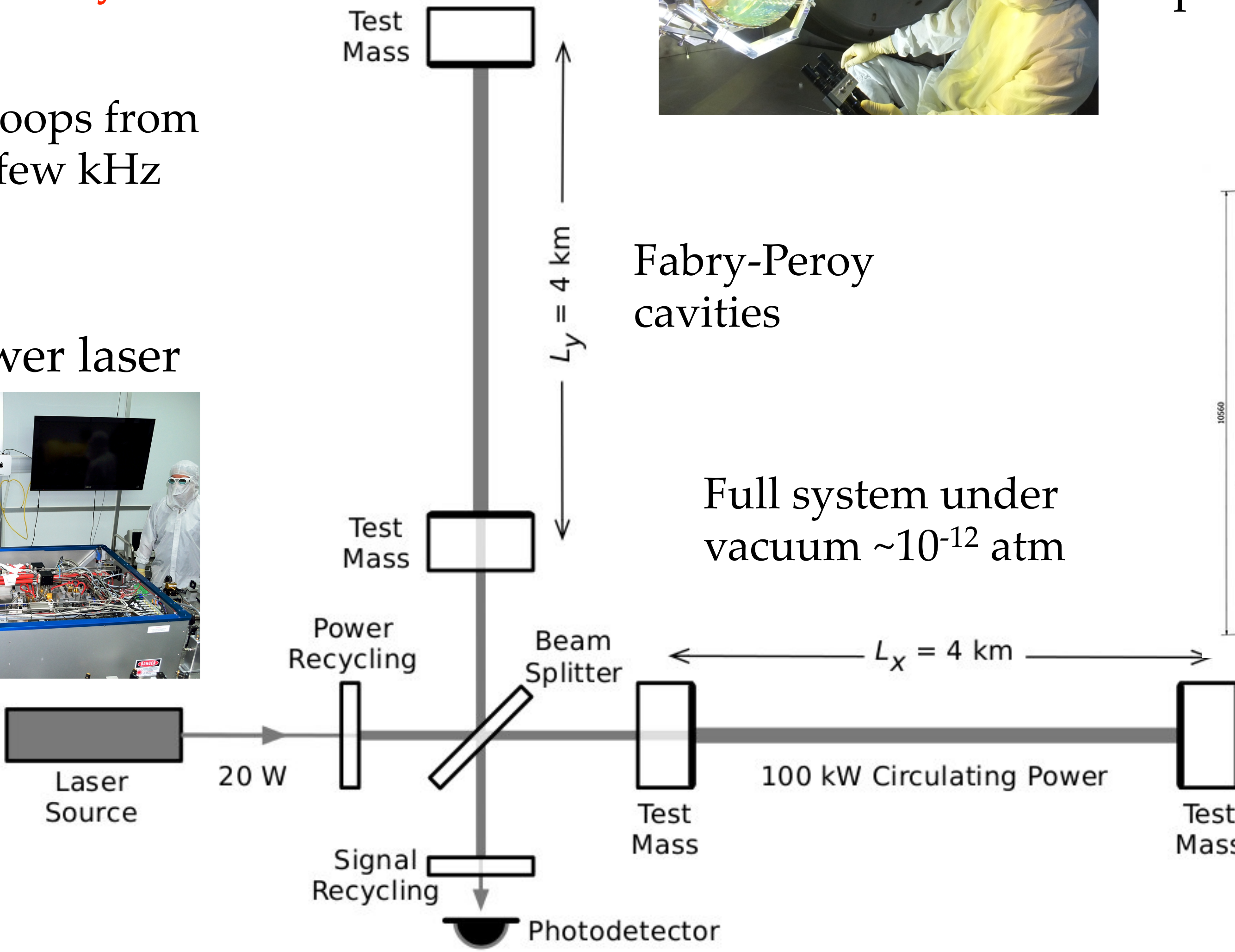
High quality optics – 40 kg

Feedback loops from few Hz to few kHz

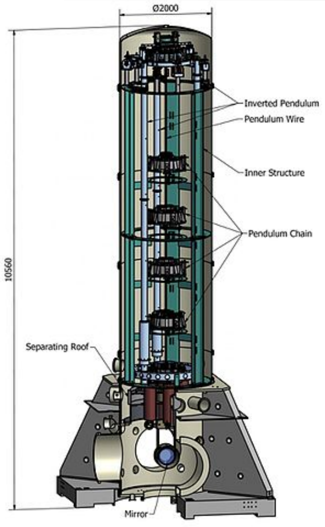
Fabry-Peroy cavities

High power laser





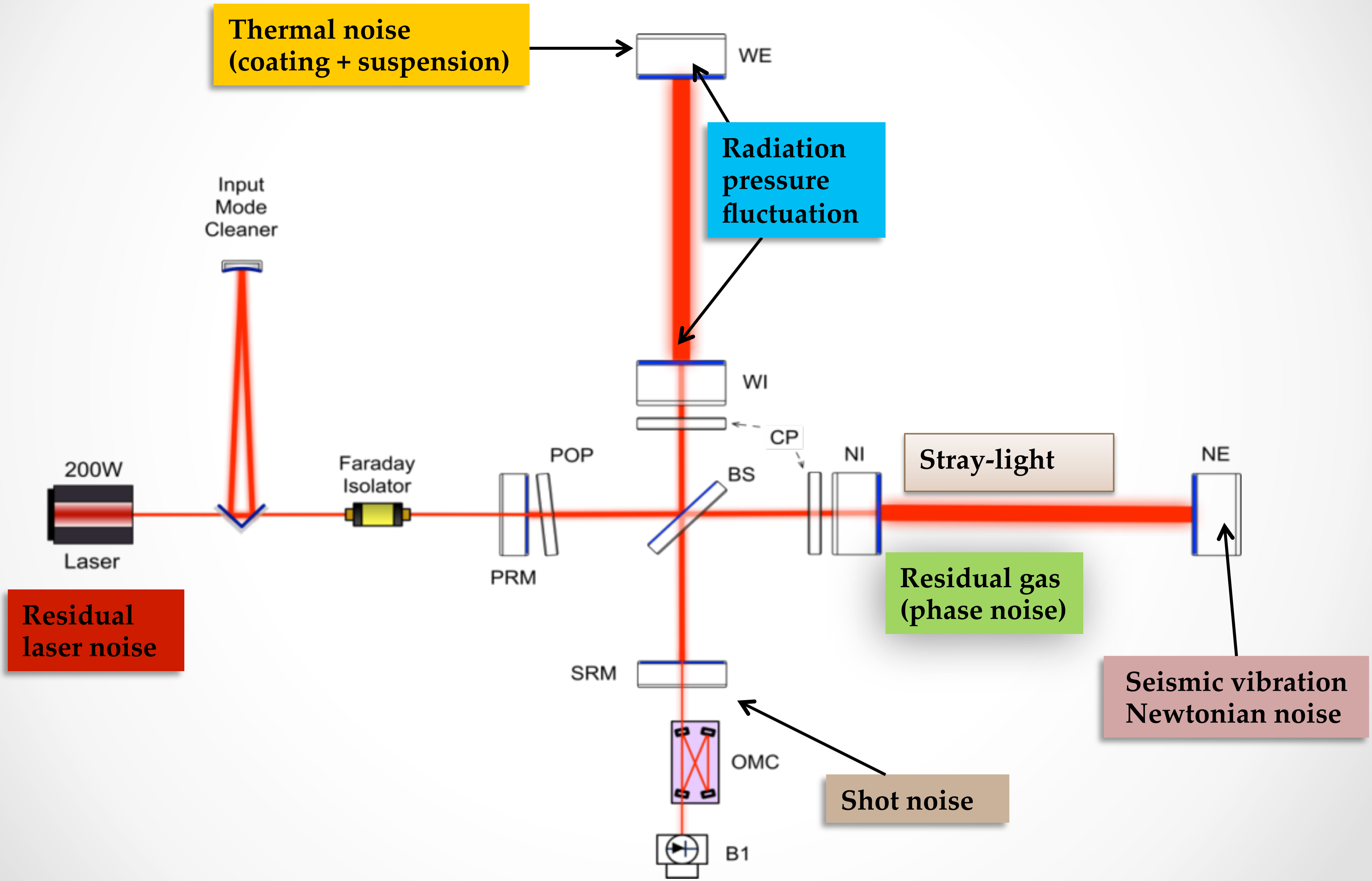
Full system under vacuum ~10^{-12} atm



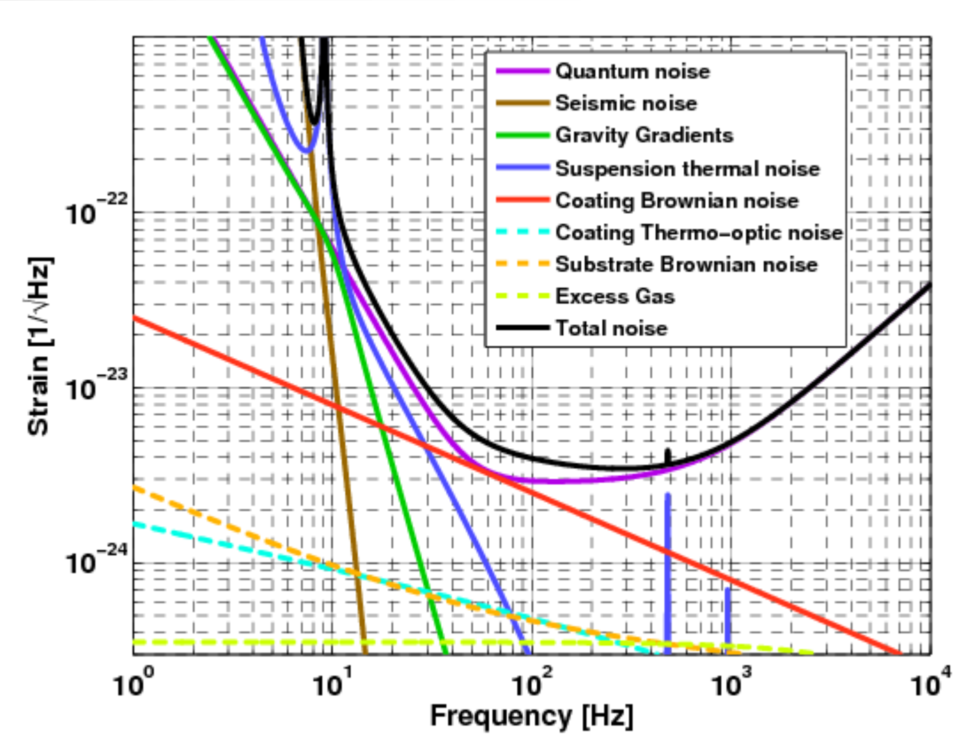
Suspended Optics

Attenuation 10^{14} @ 10 Hz

Main sources of noise



Sensitivity

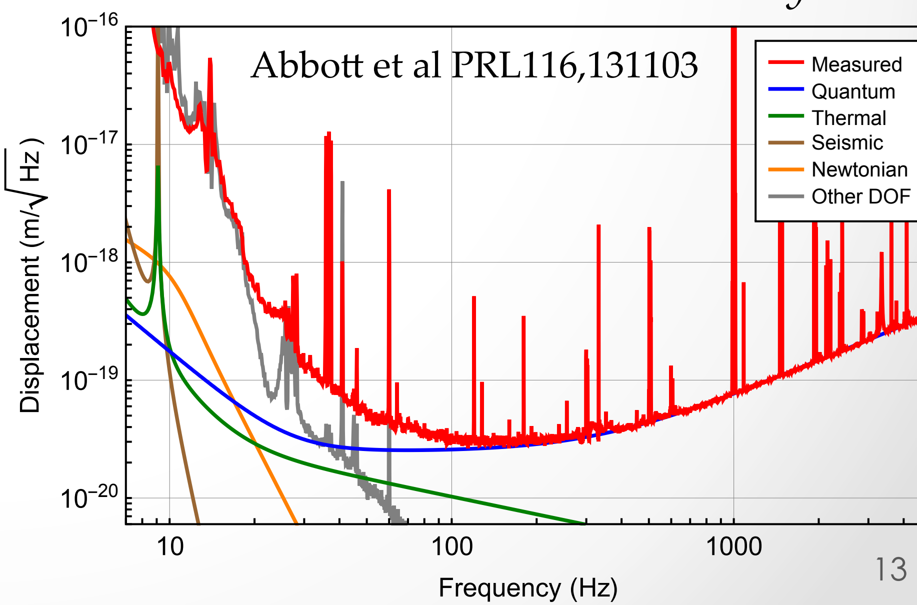


AdLIGO design sensitivity

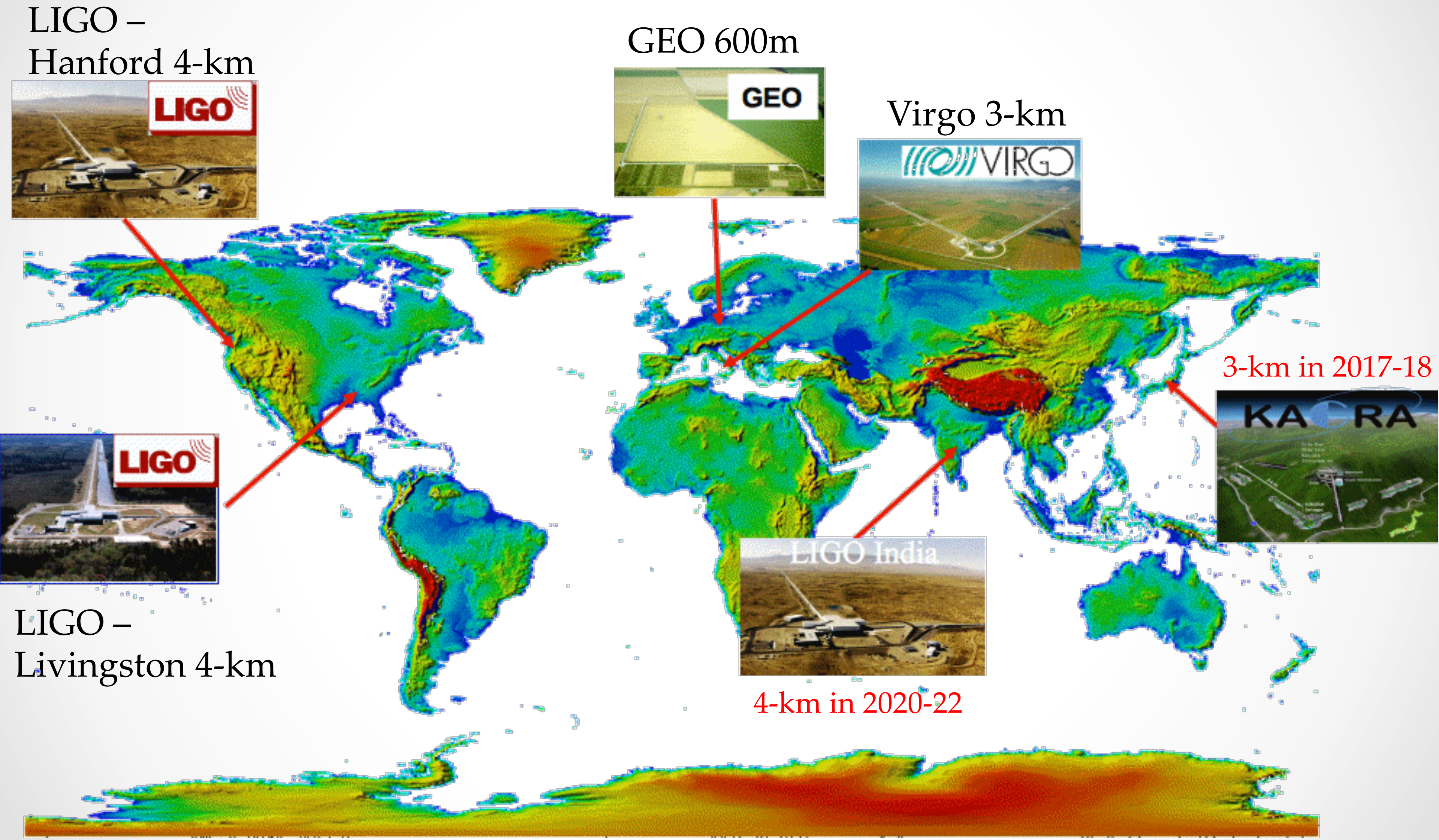
Quantum noise = error on phase measurement + fluctuation of radiation pressure

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

AdLIGO O1 sensitivity



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

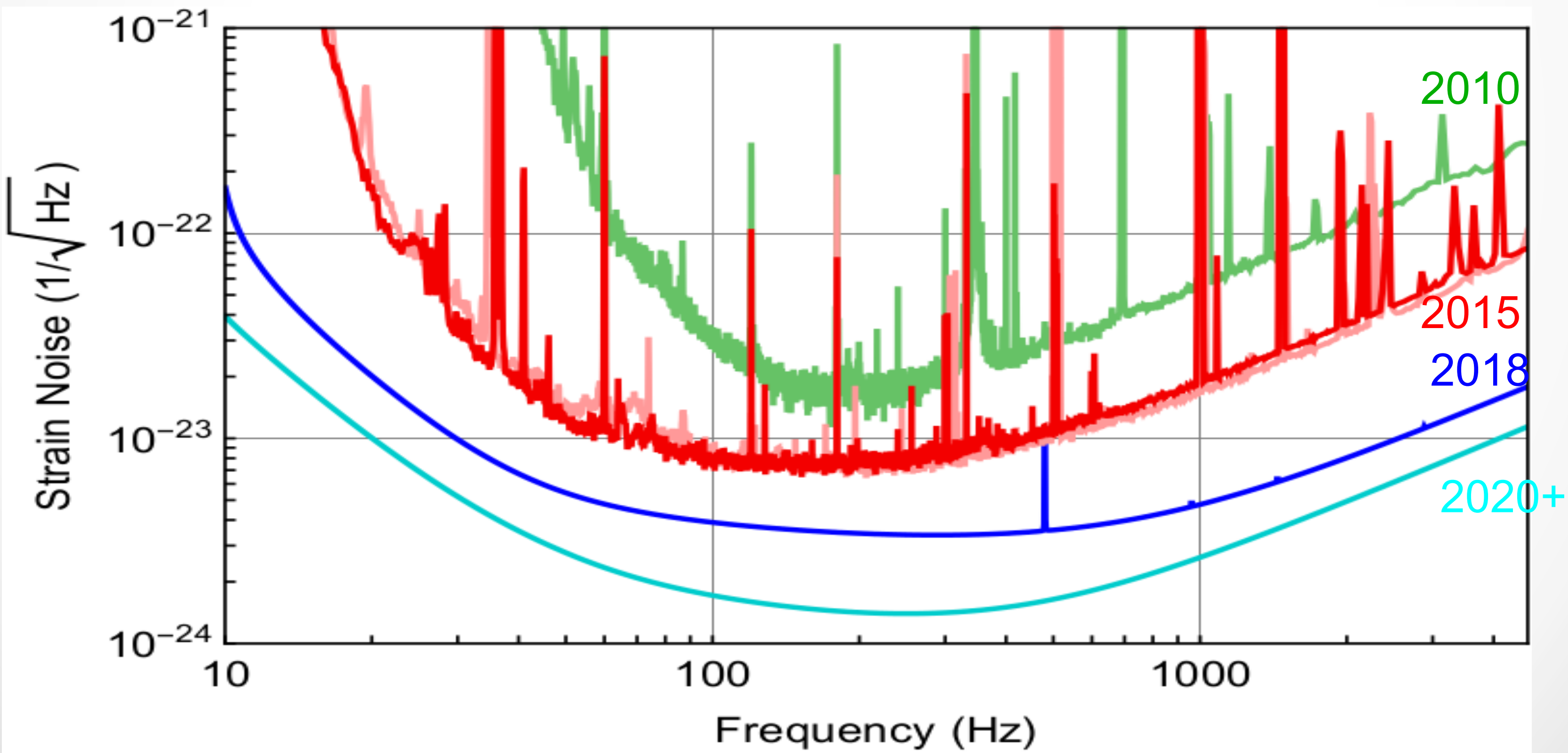
Virgo
5 countries – 200 contributors

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

Advanced LIGO run 01

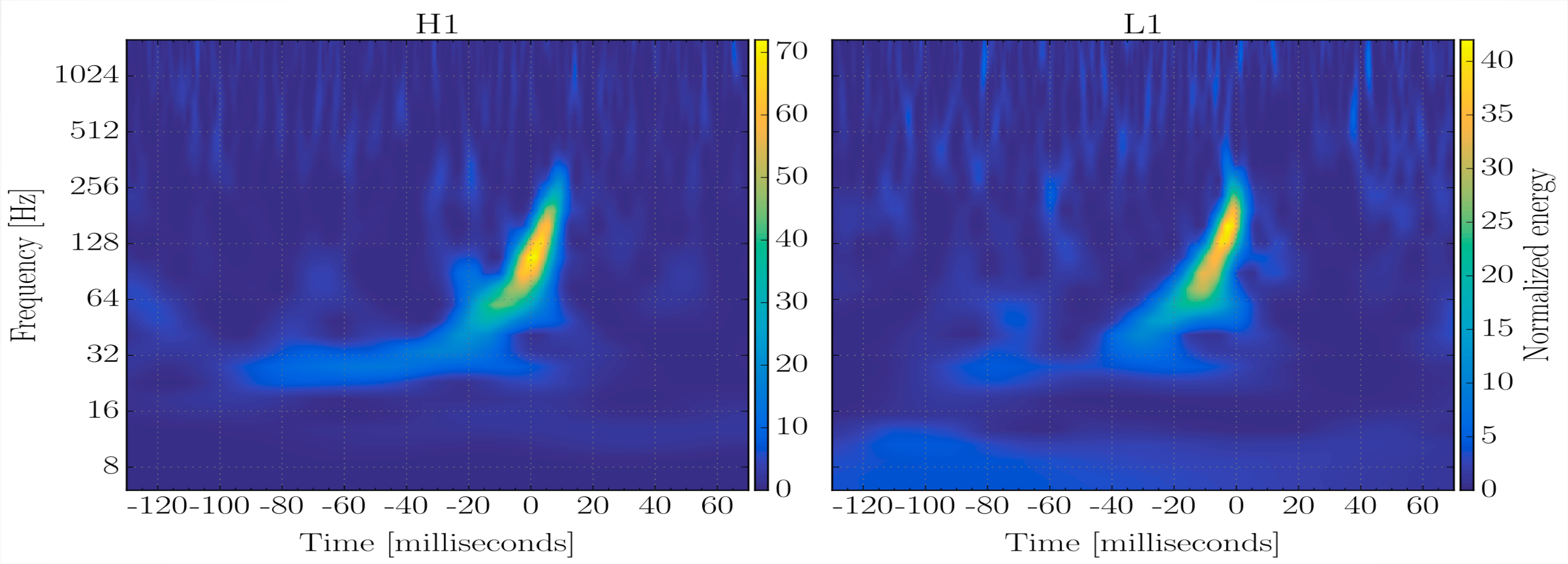
- 2010-2014: installation
- 2014-2015: commissioning
- September 2015: O1 run start!
  End Jan 19th 2016

- 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



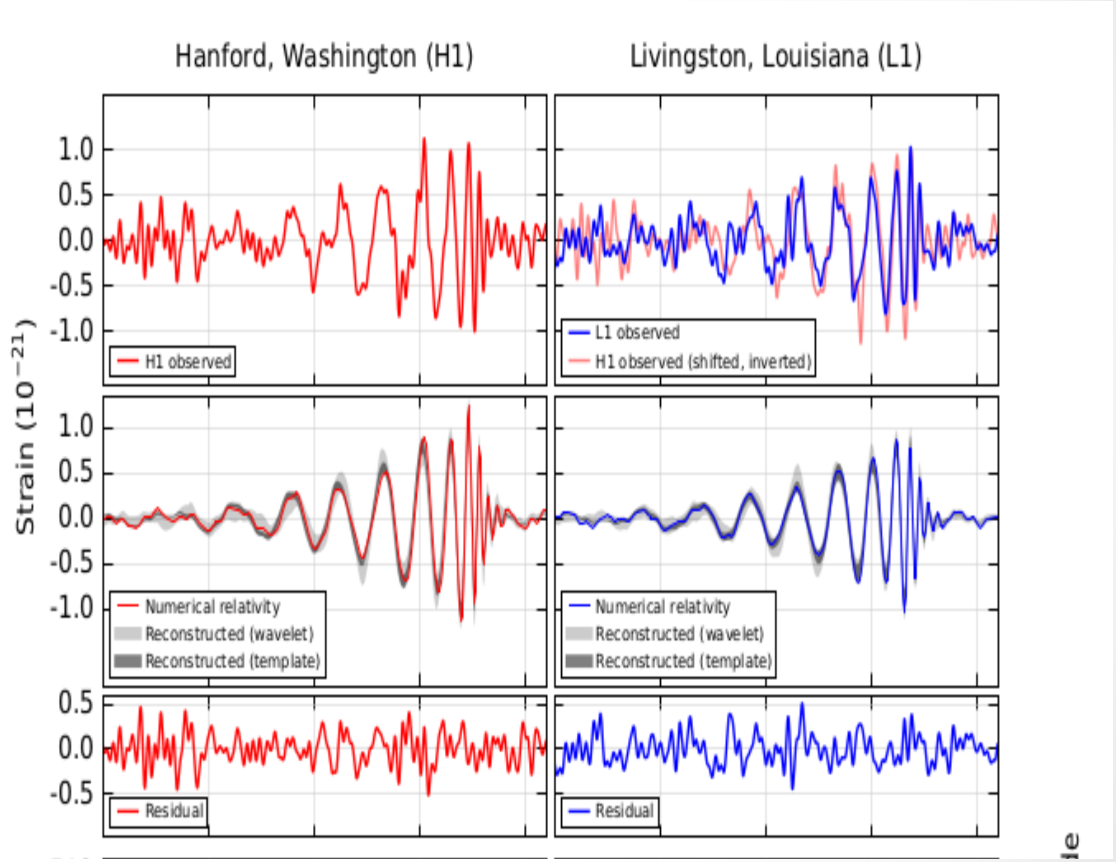
- Event reported within 3 minutes by an unmodelled search
- Within one hour, first (of a very long list) email reporting an interesting event
- In less than two hours nature and first parameters derived : BBH !!!
- Very low false alarm probability reported – message from directorate : this is not an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

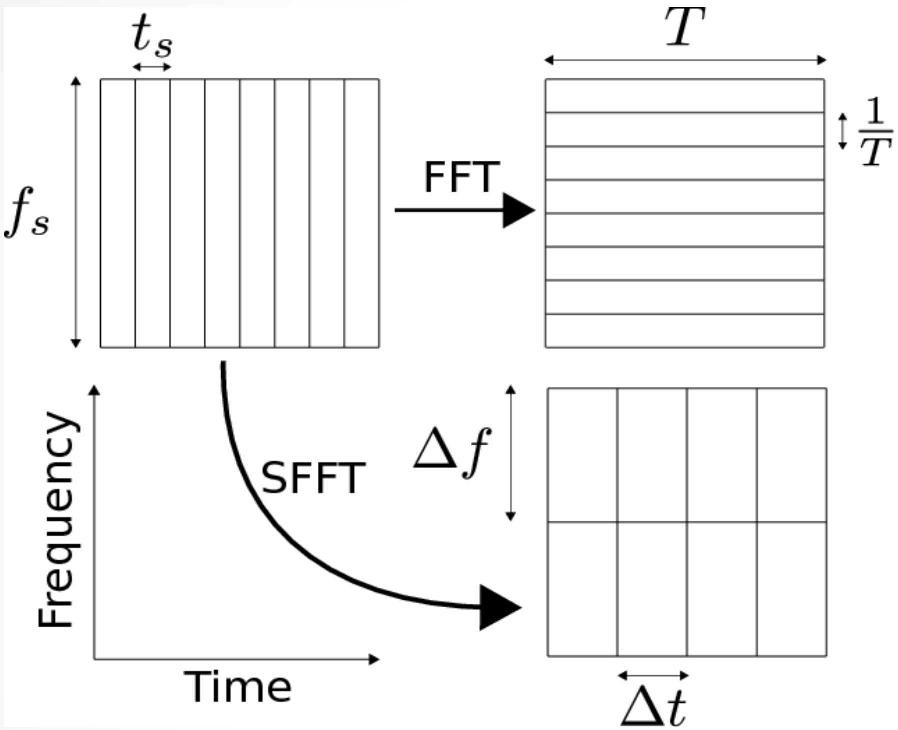
Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

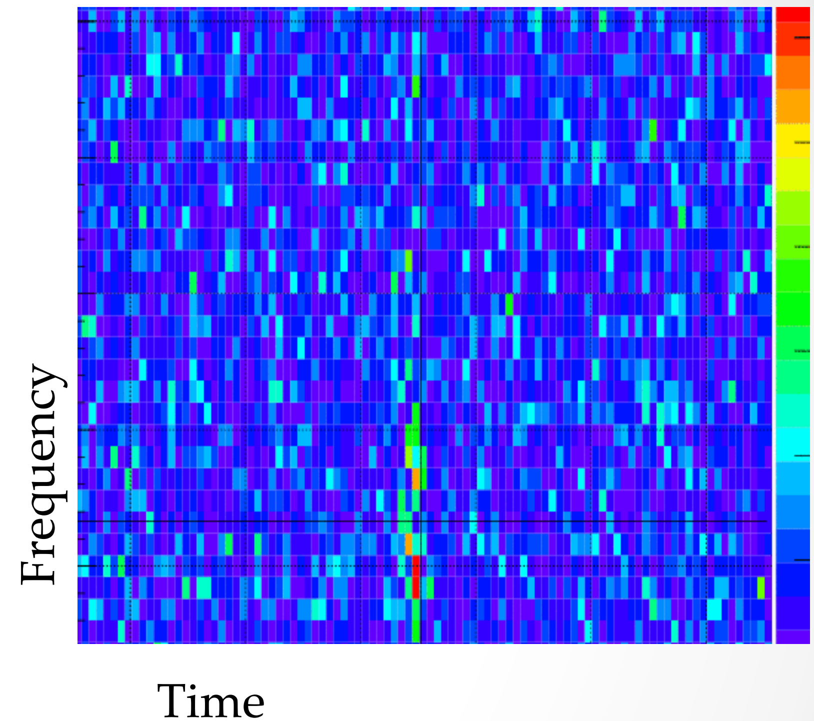
Third Row –residuals



Abbott *et al.* PRL 116, 061102

Looking for unmodelled signal





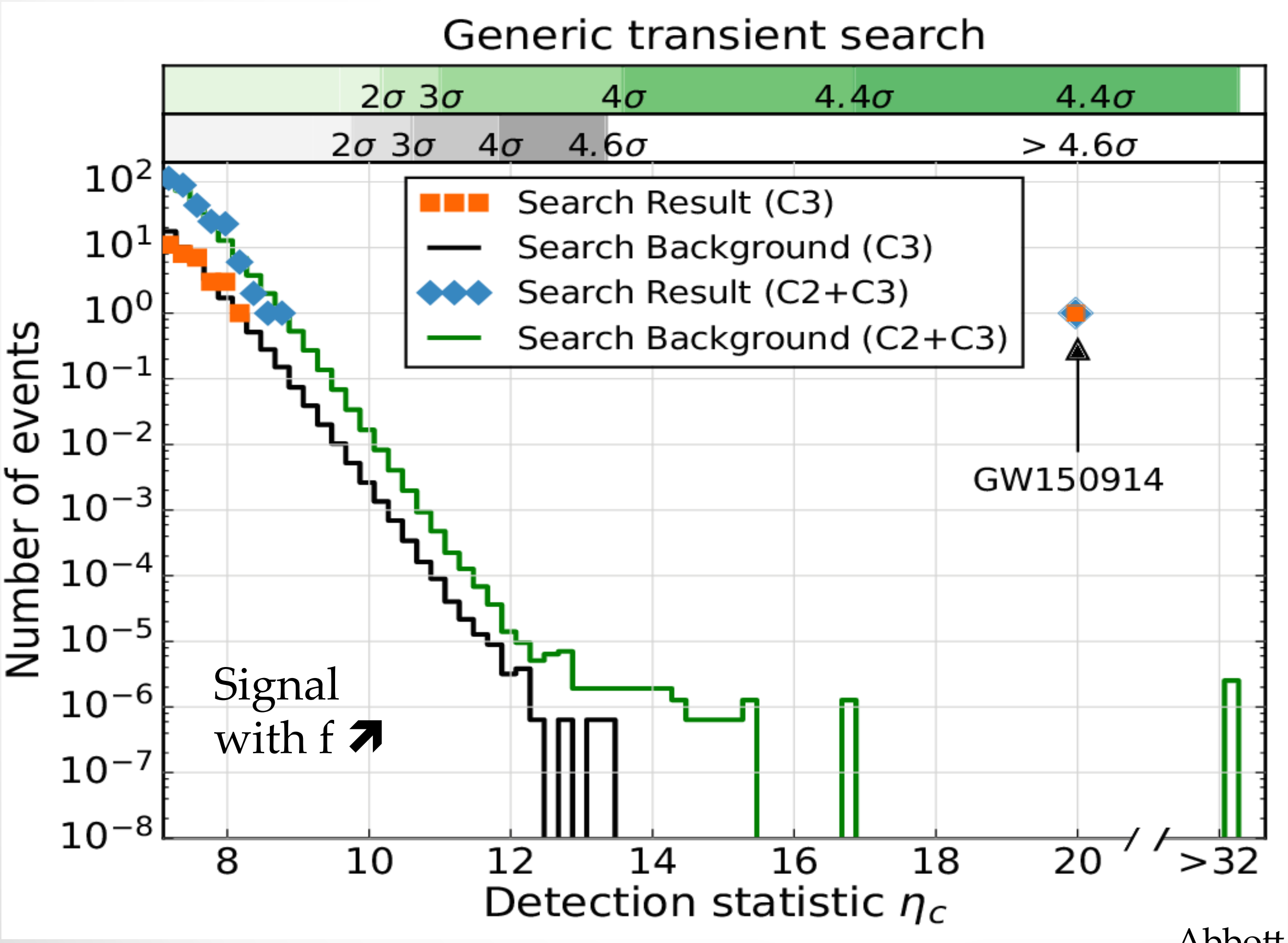
Excess in time-frequency map – using wavelet
Similar efficiency for high mass binaries (< 10 Msun)
Was running online
Background estimation with timeslides

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

Abbott *et al.* PRL 116, 061102

Search for modelled waveform

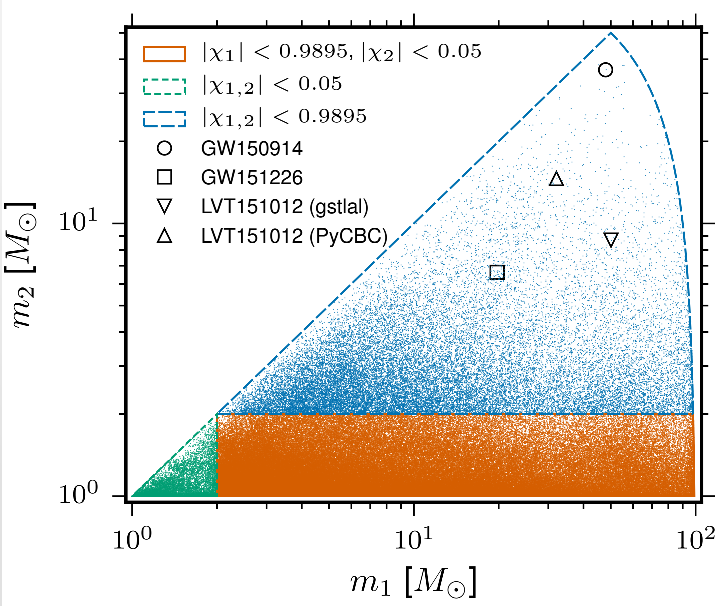
FFT of data

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, arXiv 1606.04856

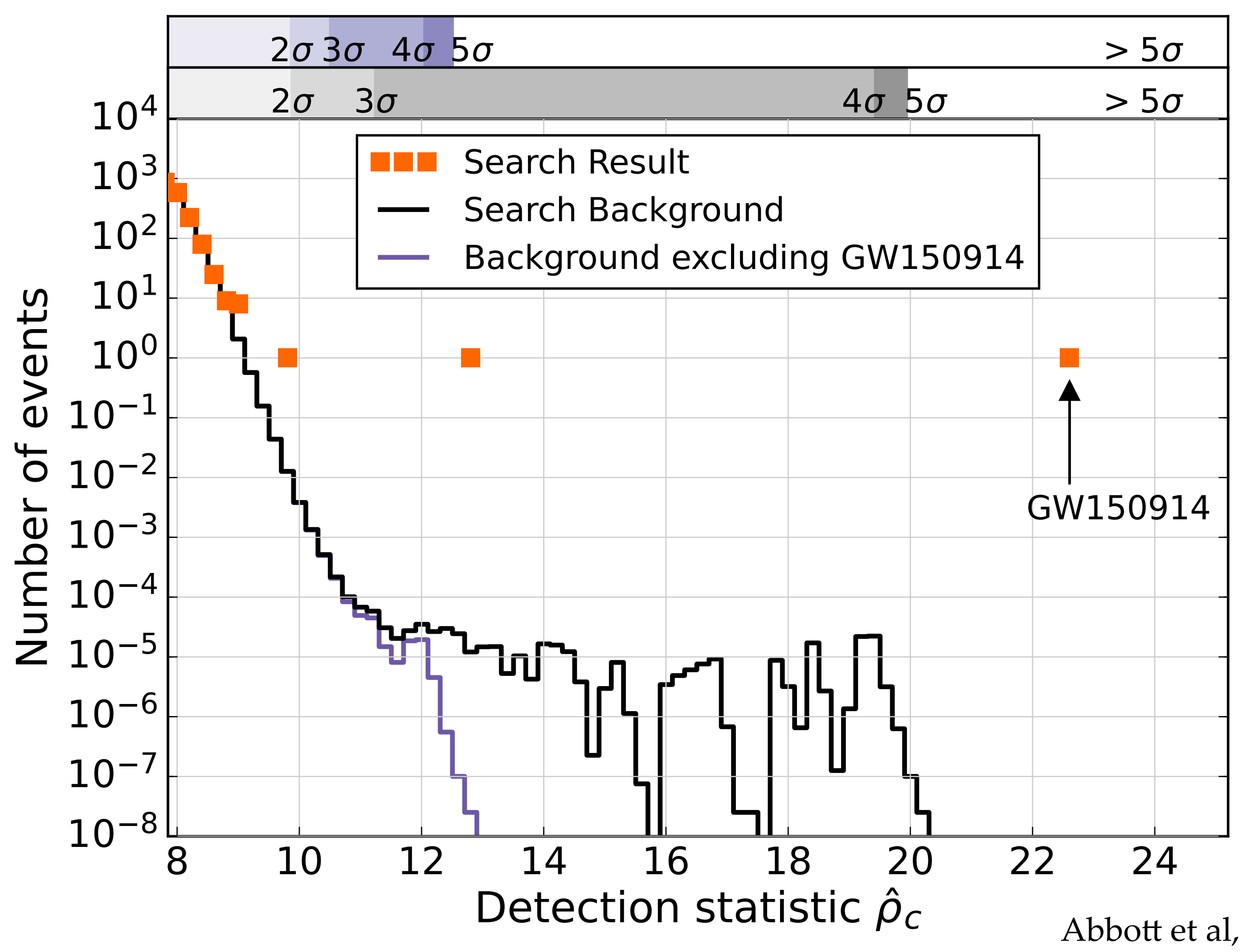


September 2015 configuration:
Waveform templates: EOBNR with aligned spins
Online: low mass regime (<20 Msun) then move to full set in October
Offline: 1-100 Msun – 250 000 templates

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



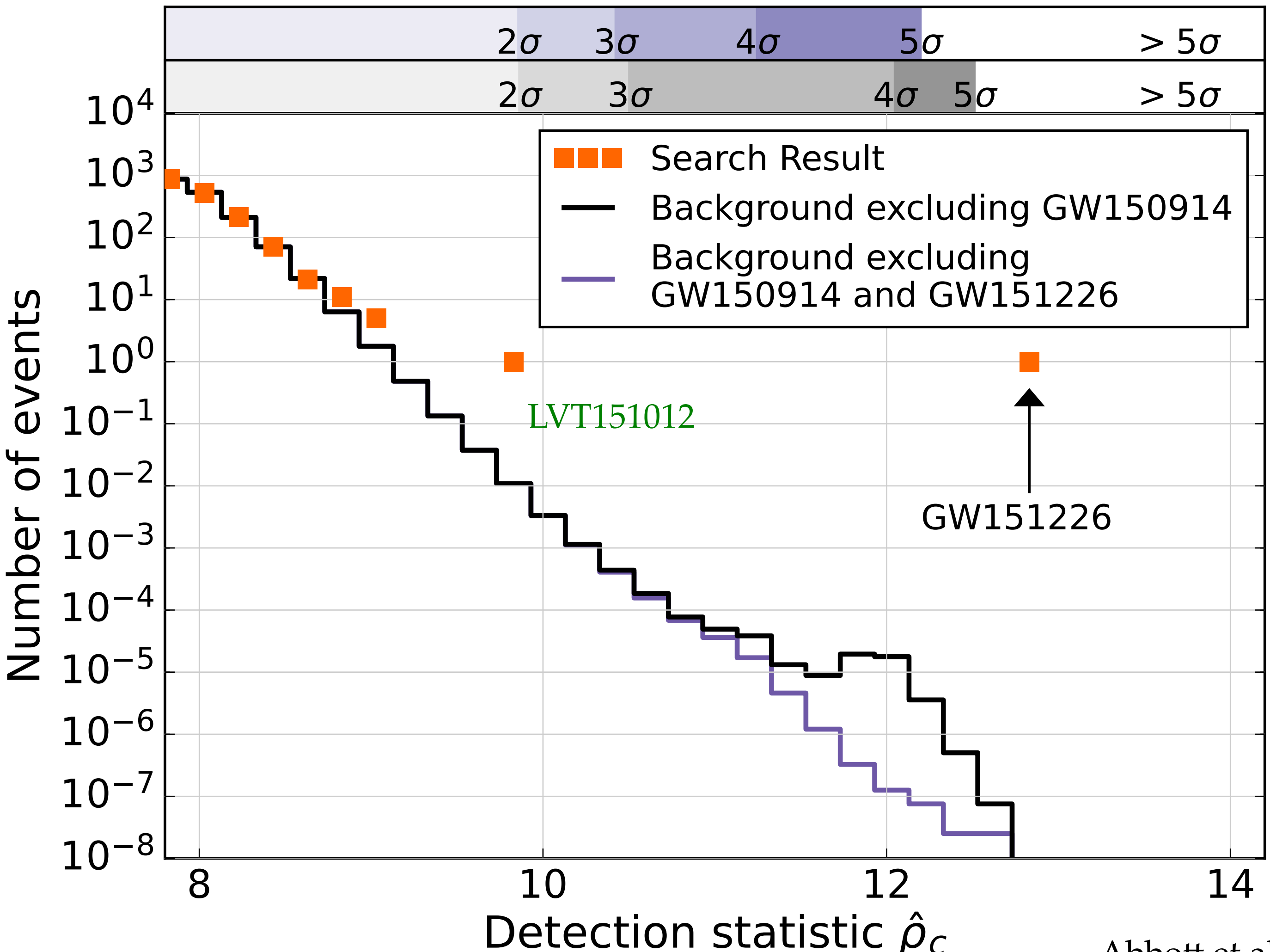
False Alarm Rate
< 1 / 200 000 years

False Alarm Prob.
< 1.1 10^{-7} - > 5.3 σ

Abbott et al, arXiv 1606.04856

Results for BBH search during O1

using match filtering



False Alarm Rate
< 1 / 200 000 years

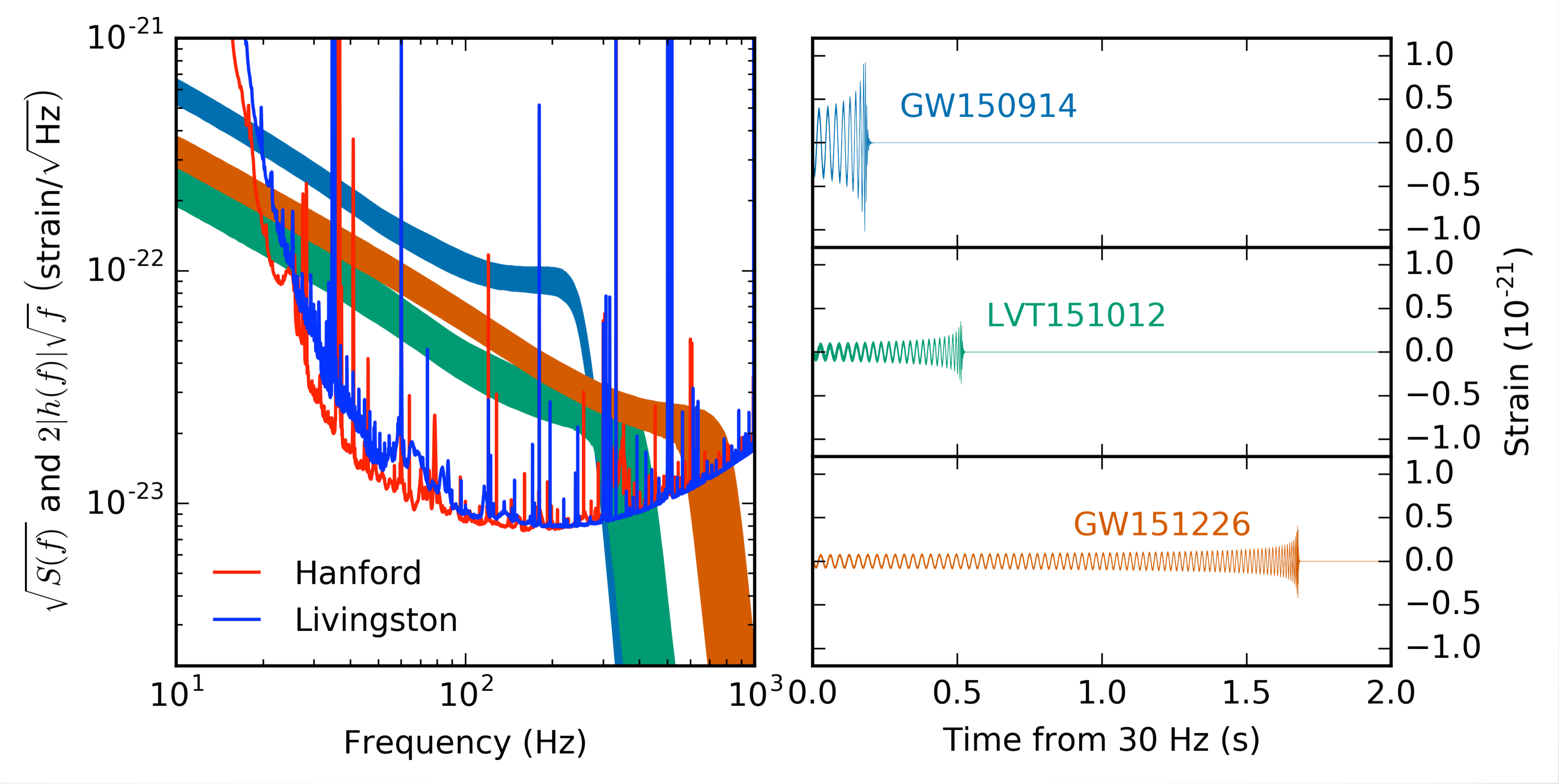
False Alarm Prob.
< 1.1 10^{-7} - > 5.3 σ

LVT151012
1.7 σ

Abbott et al, arXiv 1606.04856

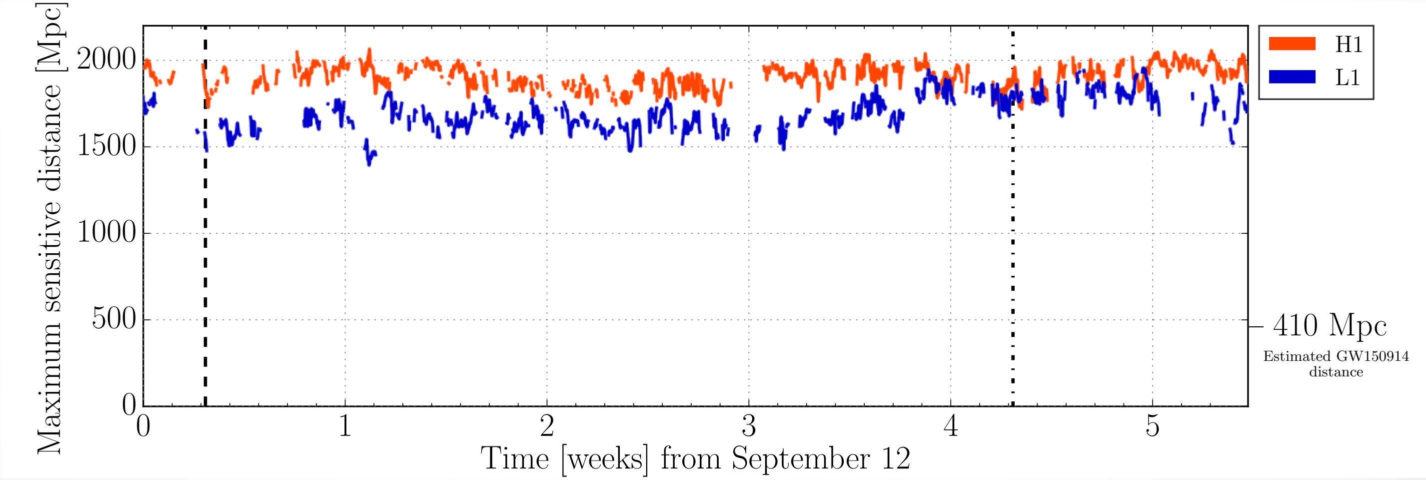
Comparing the signals

Abbott et al, arXiv 1606.04856



Can it be something else?

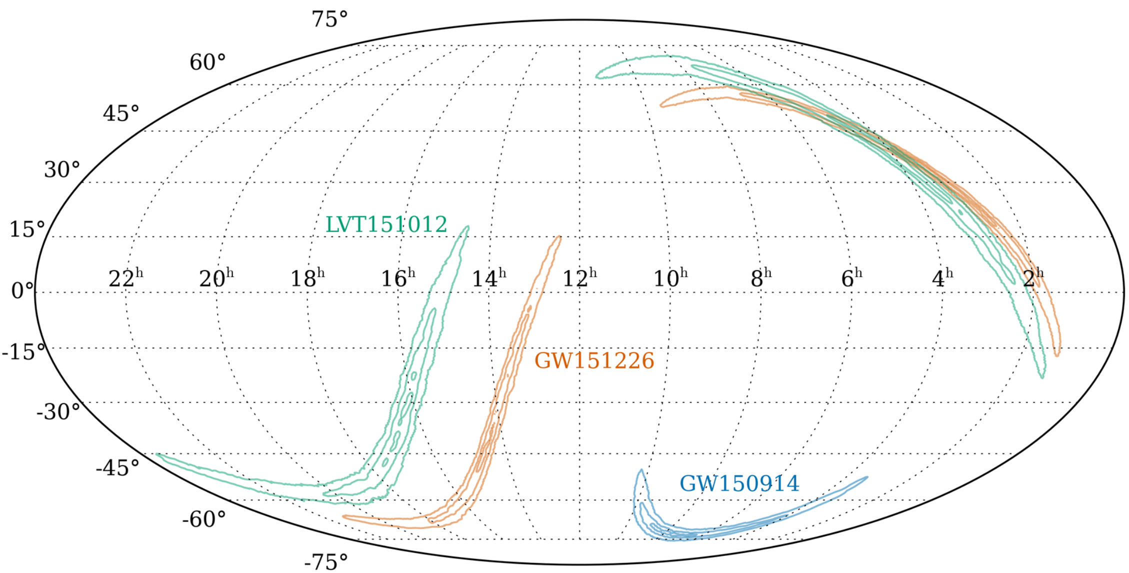
- Noise investigation: 200,000 auxiliary channels scrutinized
  - Un-correlated noise: anthropogenic, earthquakes, radio-frequency modulation, unknown origin / known family glitches.
  - Correlated noise: potential EM noise sources (lightning exciting Schumann resonances, solar wind, …).
- Detector's 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

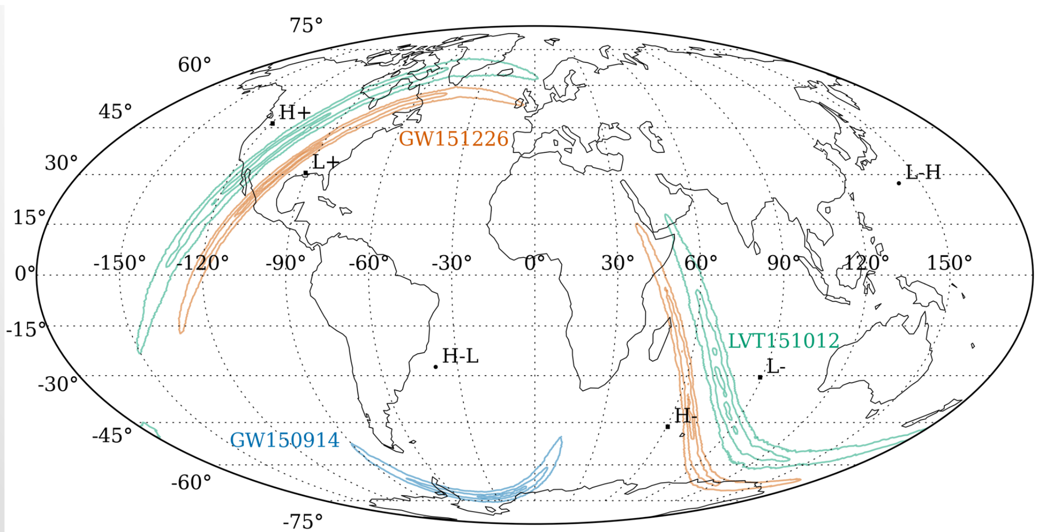


Abbott *et al.* CQG 33, 13, 134001

Sky location

Abbott et al, arXiv 1606.04856



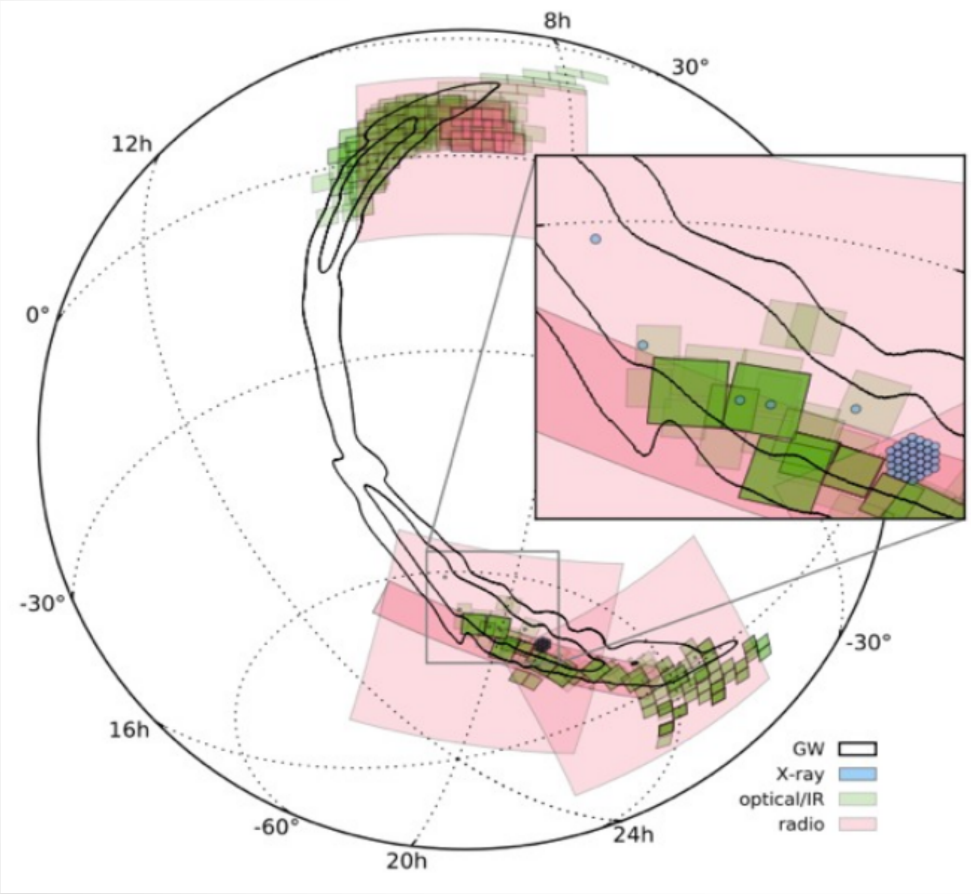


230 sq deg
850 sq deg
1600 sq deg

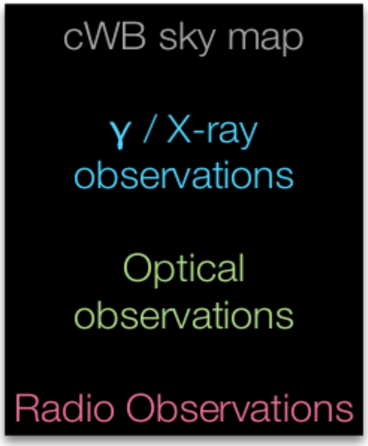
different pipelines with different assumptions got similar results

Follow-up with externals 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

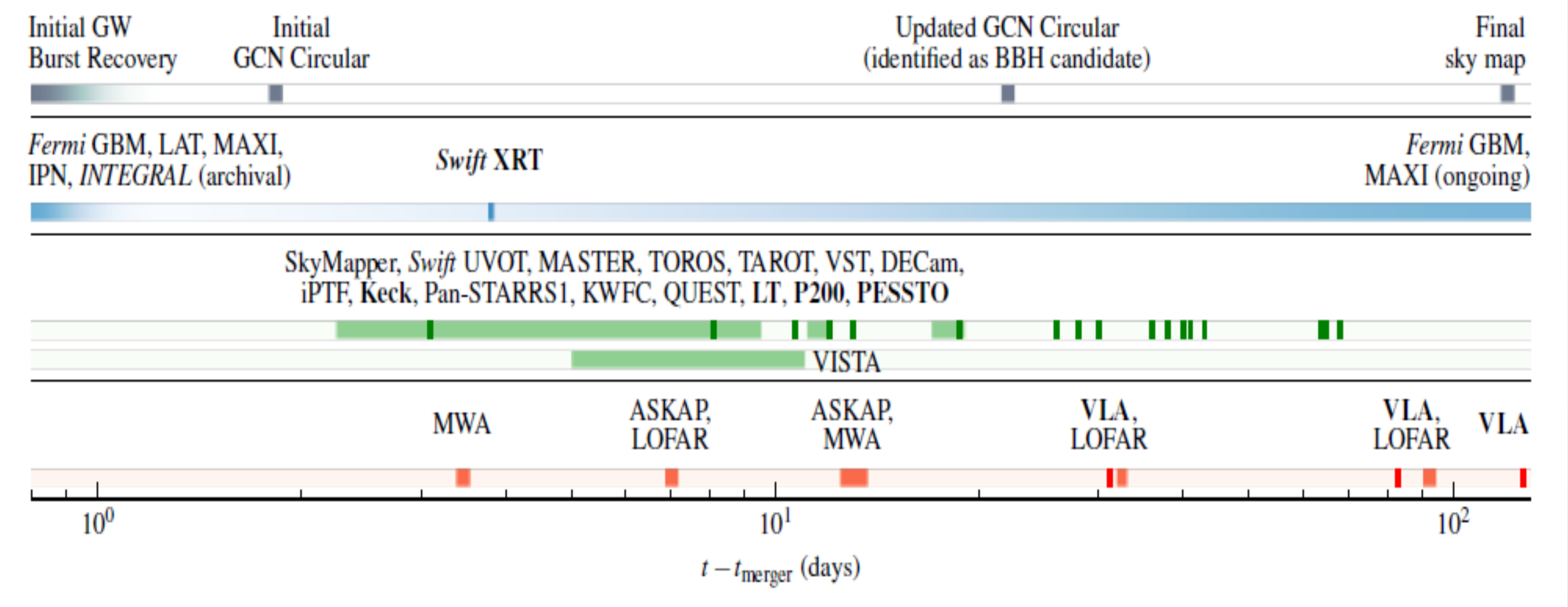


External observatories first focus on BNS systems

Follow-up with externals observatories

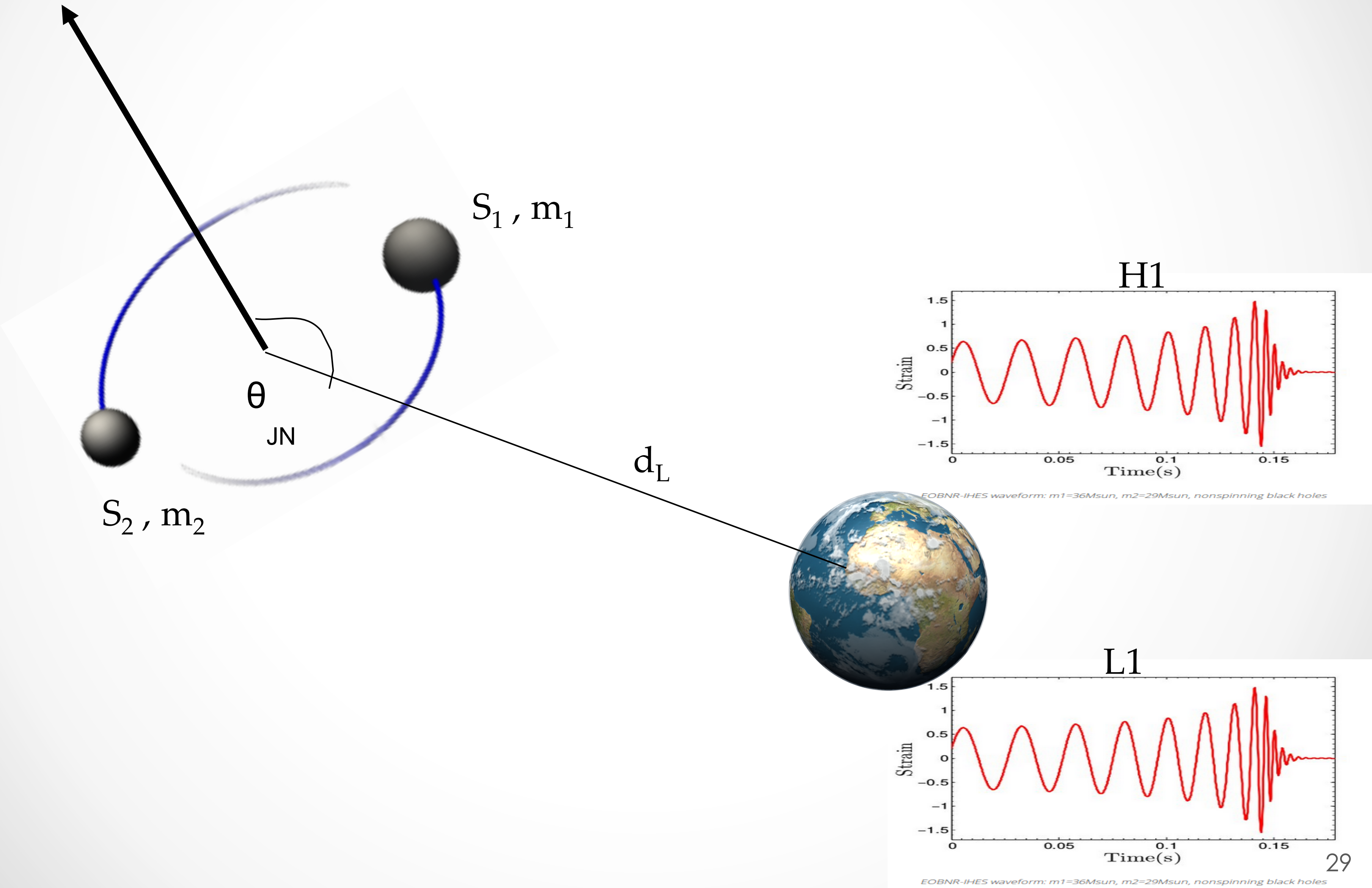
Abbott *et al.* ApJL vol. 826 pg. L13

GW150914 example



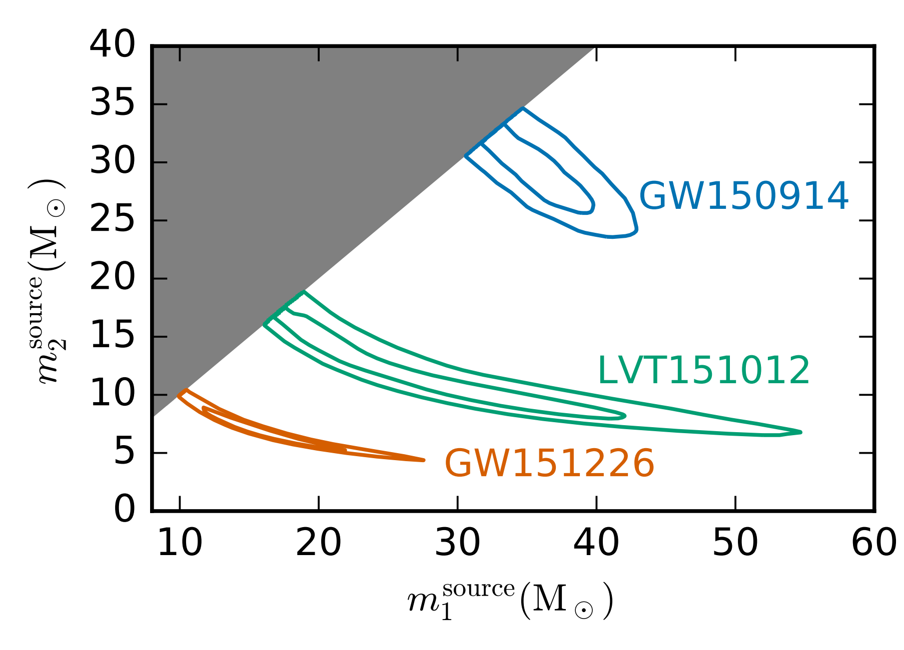
No clear signal yet reported

Parameters of the sources

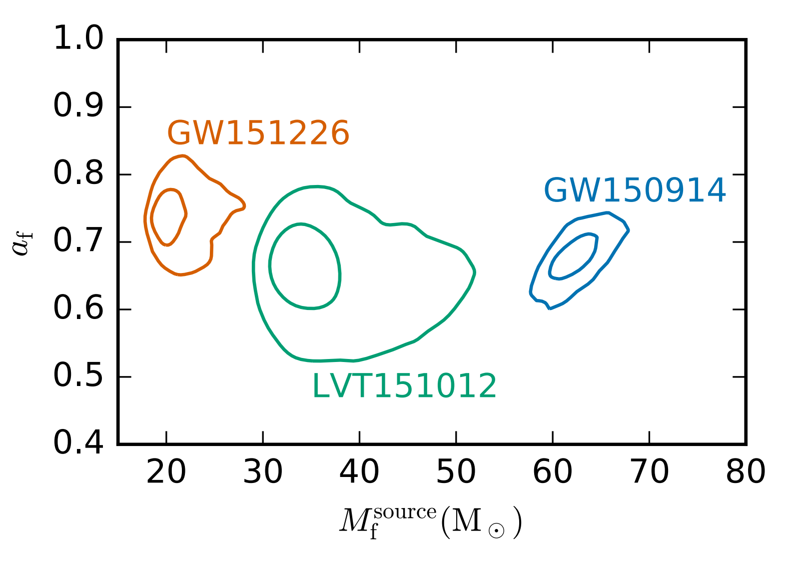


Parameters inference

Abbott et al, arXiv 1606.04856



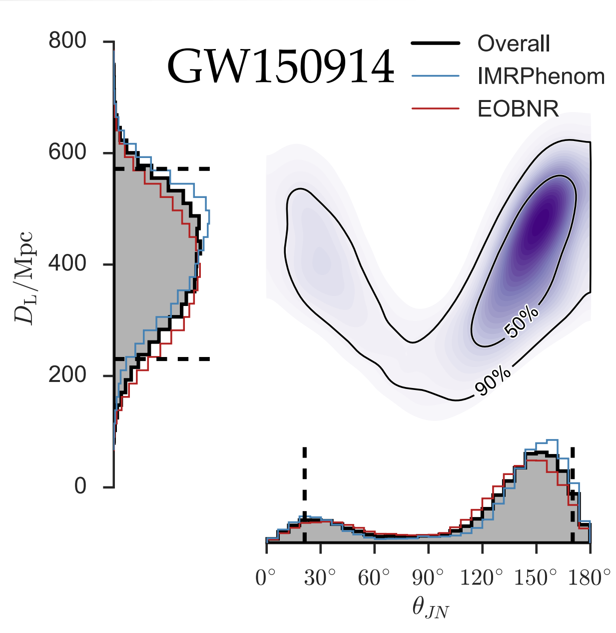
Initial masses



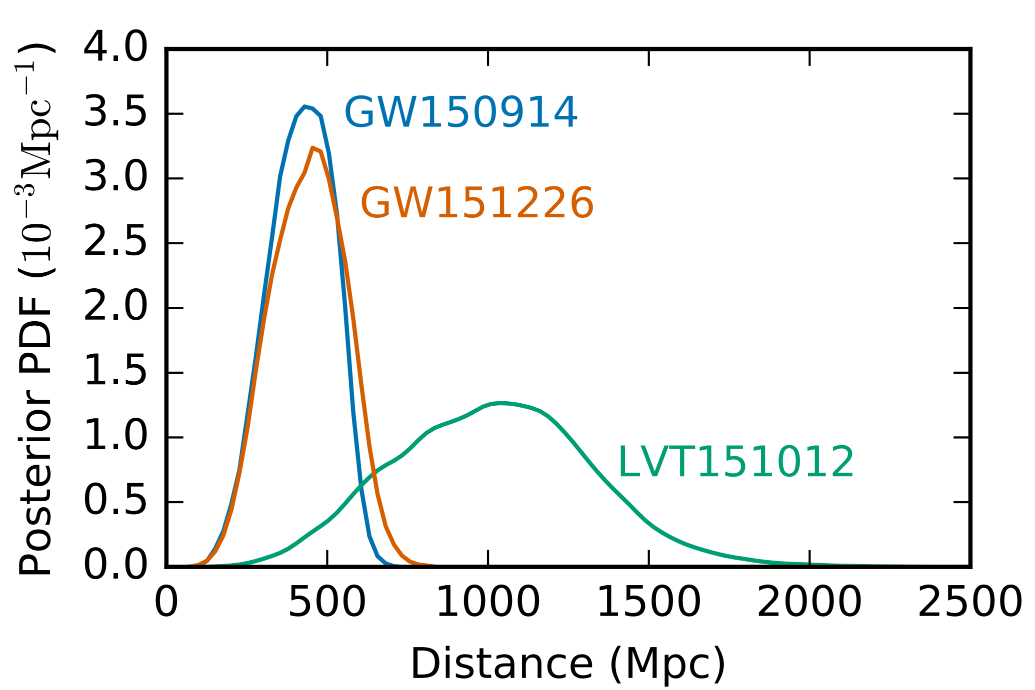
Final mass and spin

Parameters inference

Abbott et al, PRL 116, 241102



Distance vs inclination angle have correlation



Abbott et al, arXiv 1606.04856

Main parameters

Abbott et al, arXiv 1606.04856

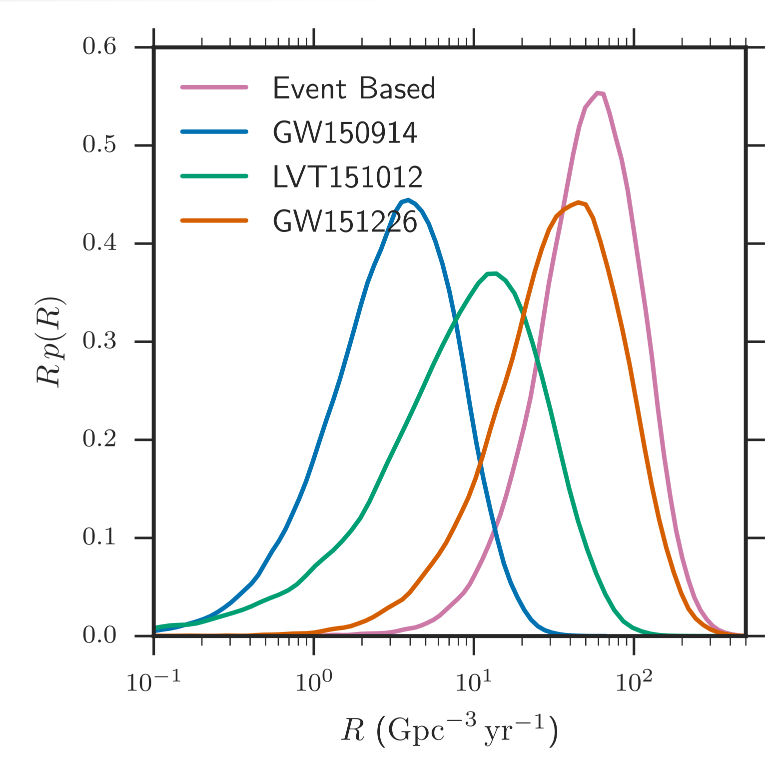
Event	GW150914	GW151226
Primary mass $m_1^{\rm source}/{\rm M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$
Chirp mass $\mathscr{M}^{\rm source}/{\rm M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$
Total mass $M^{\rm source}/{\rm M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$
Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$
Final spin $a_{\rm f}$	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$

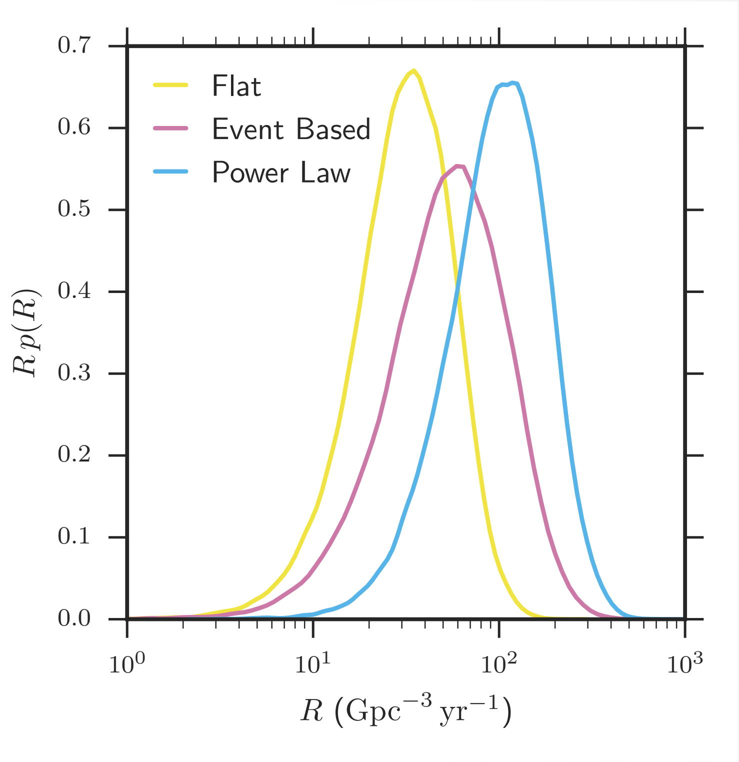
Event	GW150914	GW151226
Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$

- GW150914 is compatible with a coalescence of 2 black holes with similar mass
- 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, arXiv 1606.04856

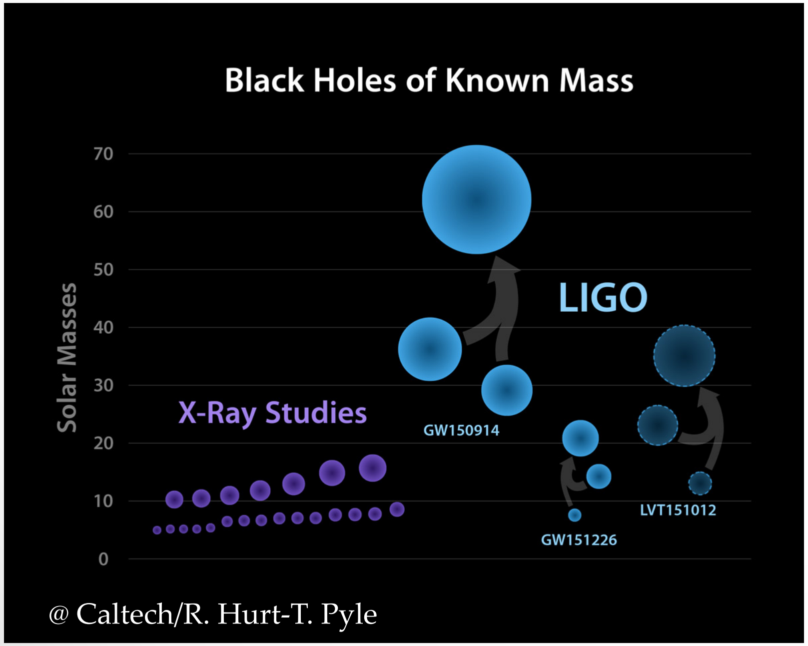


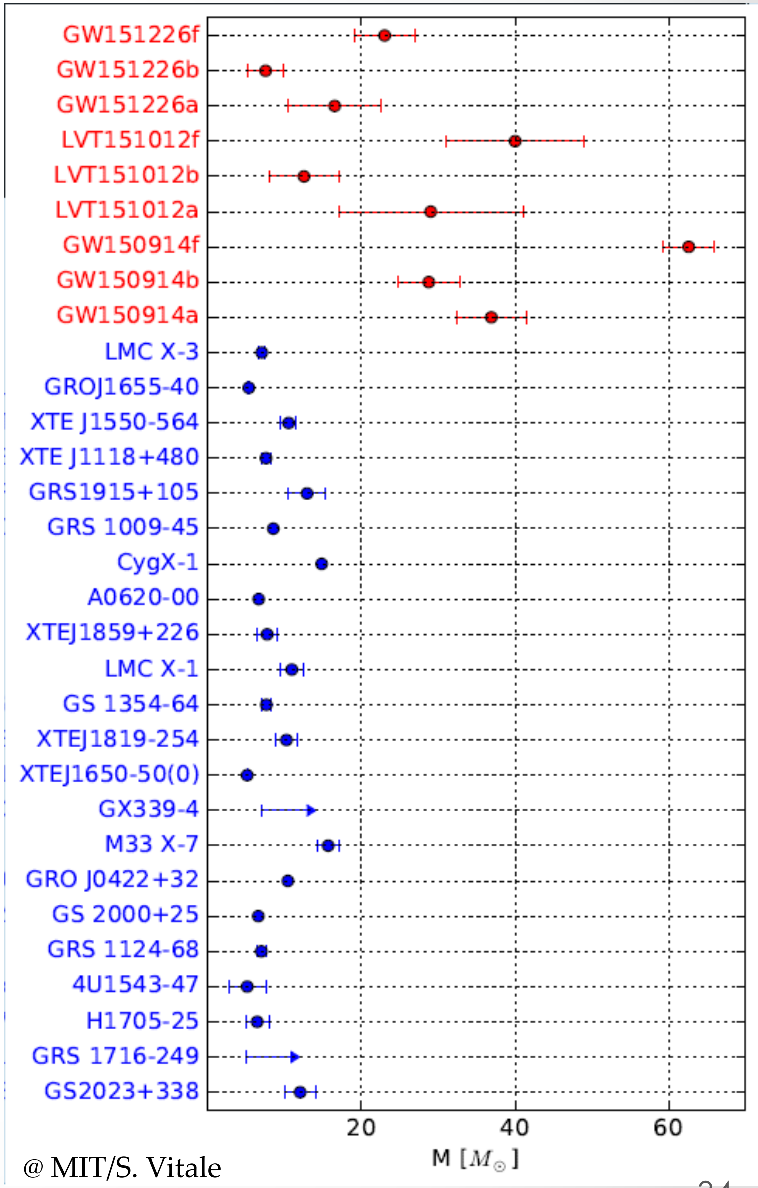


- Assuming constant volume up to horizon (z~0.5)
- Different distributions
- Using all infos R = 9 – 250 Gpc $^{-3}$ yr $^{-1}$

Black hole population ?

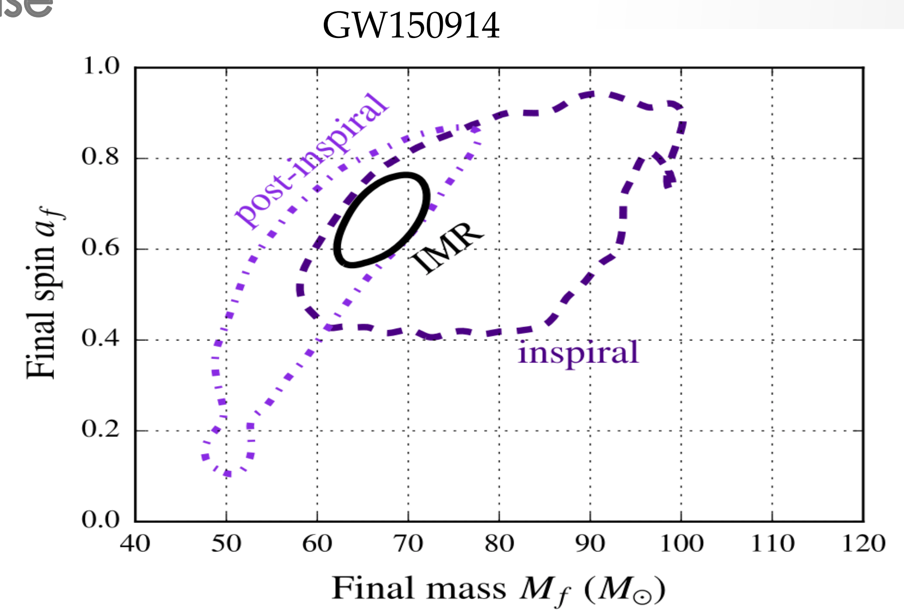
- Events observed are much heavier than what has been observed in X-rays binaries
- Not yet possible to distinguish between isolated binaries or capture in dense environment (globular clusters, galaxies center, …
- Favor low metallicity stars and then weak massive-stars wind





Testing General relativity in a new regime

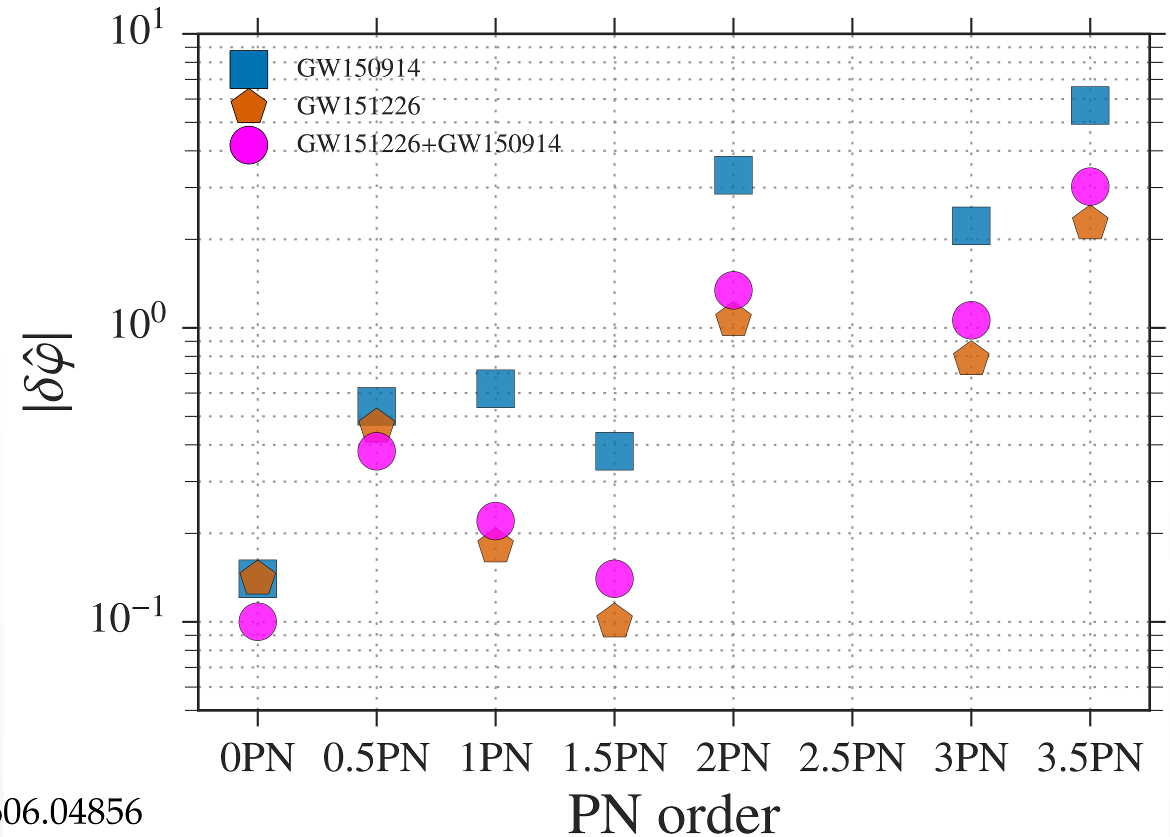
- We have for the first time test under highly relativistic and non linear conditions
- Different tests can be peformed :
    - Remove waveform and see any deviation from noise in the data : possible deviations less than 4 %
    - Check the consistency of the waveform if:
        - Look only the pre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



Abbott *et al.* PRL 116, 221101

Constraining parametrization deviations

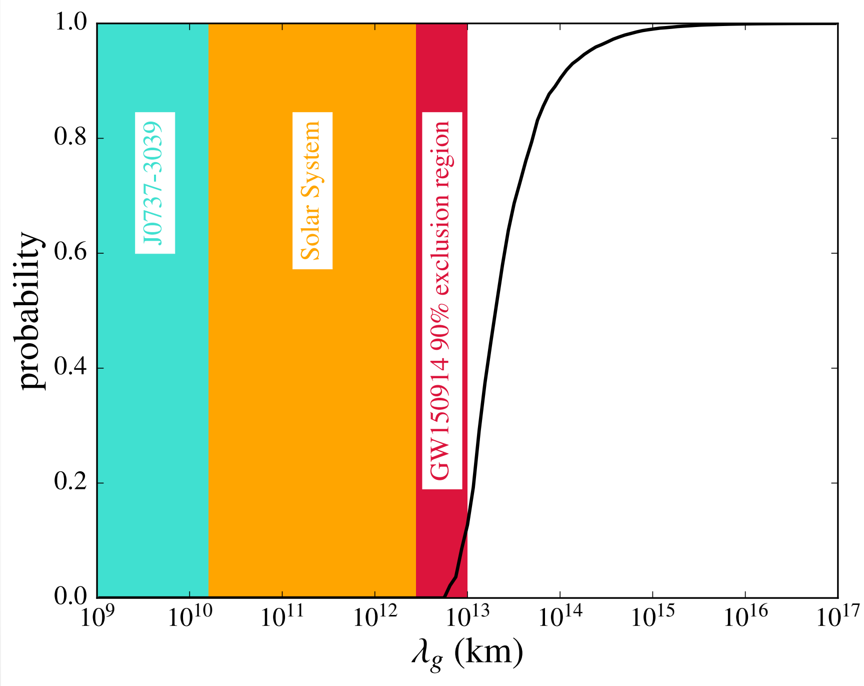
- We can test any non linear deviation to GR
- Using the complete waveform it then possible to test any deviation in the different orders of the post-Newtonian development of the waveforms with phase evolution



Abbott et al, arXiv 1606.04856

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



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

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

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

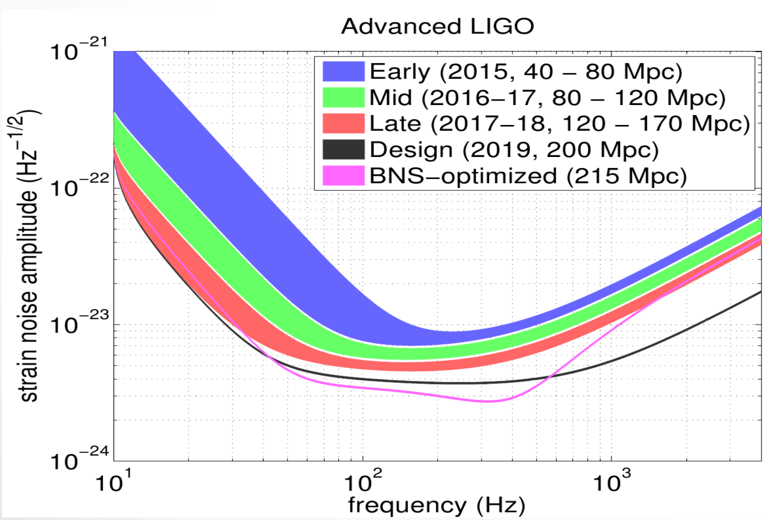
$$m_g < 10^{-22} eV$$

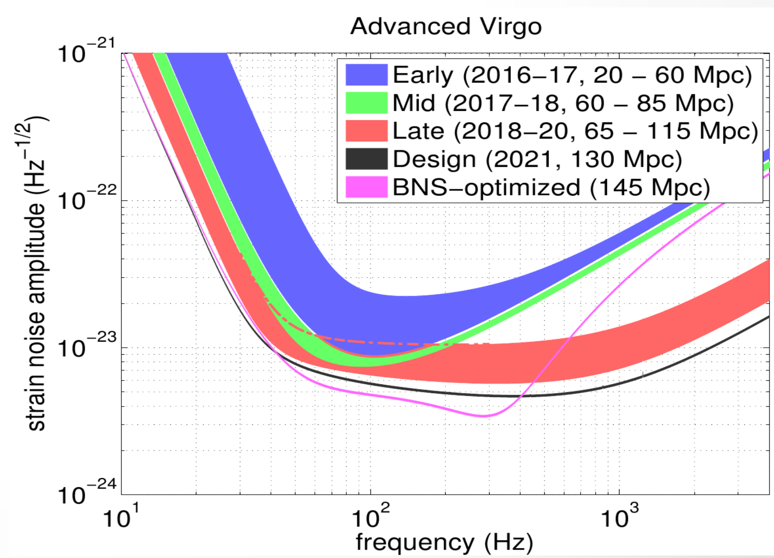
Abbott *et al.* PRL 116, 221101

LIGO and Virgo in the next months

- Next data taking this September– will extend up to first half of 2017
- Virgo is still in installation/commisioning and will try to join this run – beginning of 2017
- 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

Abbott et al, Living Reviews in Relativity 19, 1

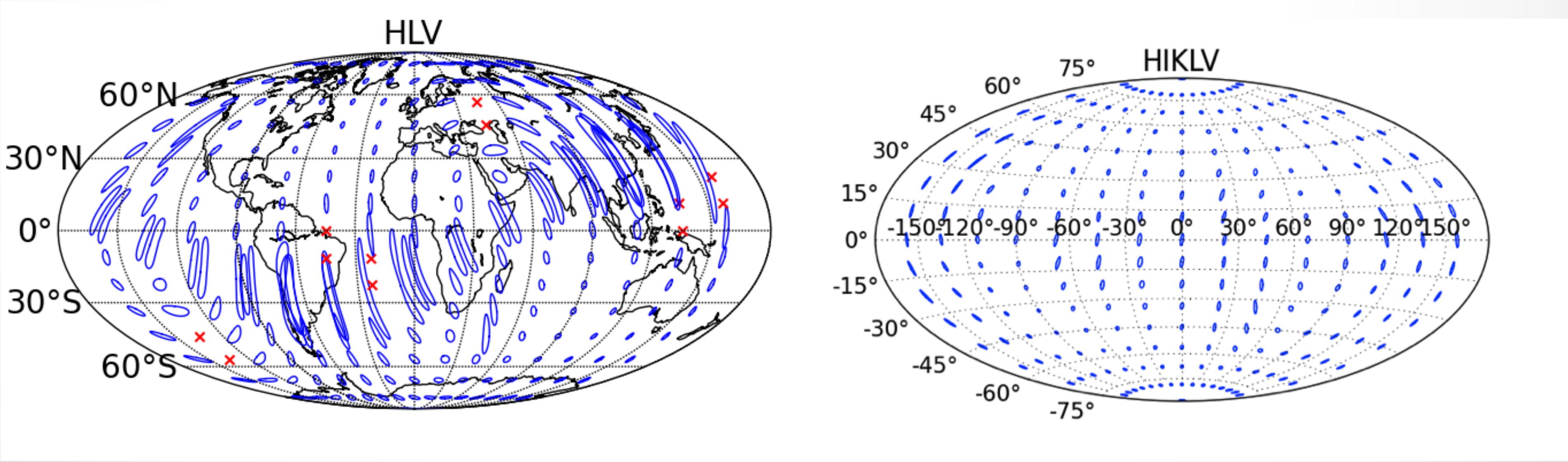




New detectors not far away

- KAGRA is well advanced – we may have comparable sensitivity before 2018 (?) – 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

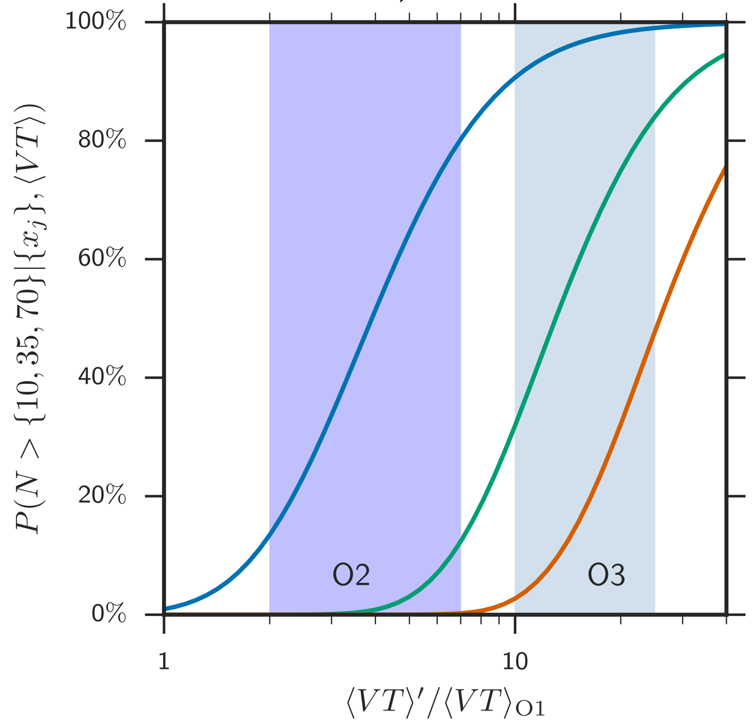
At the end

- 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

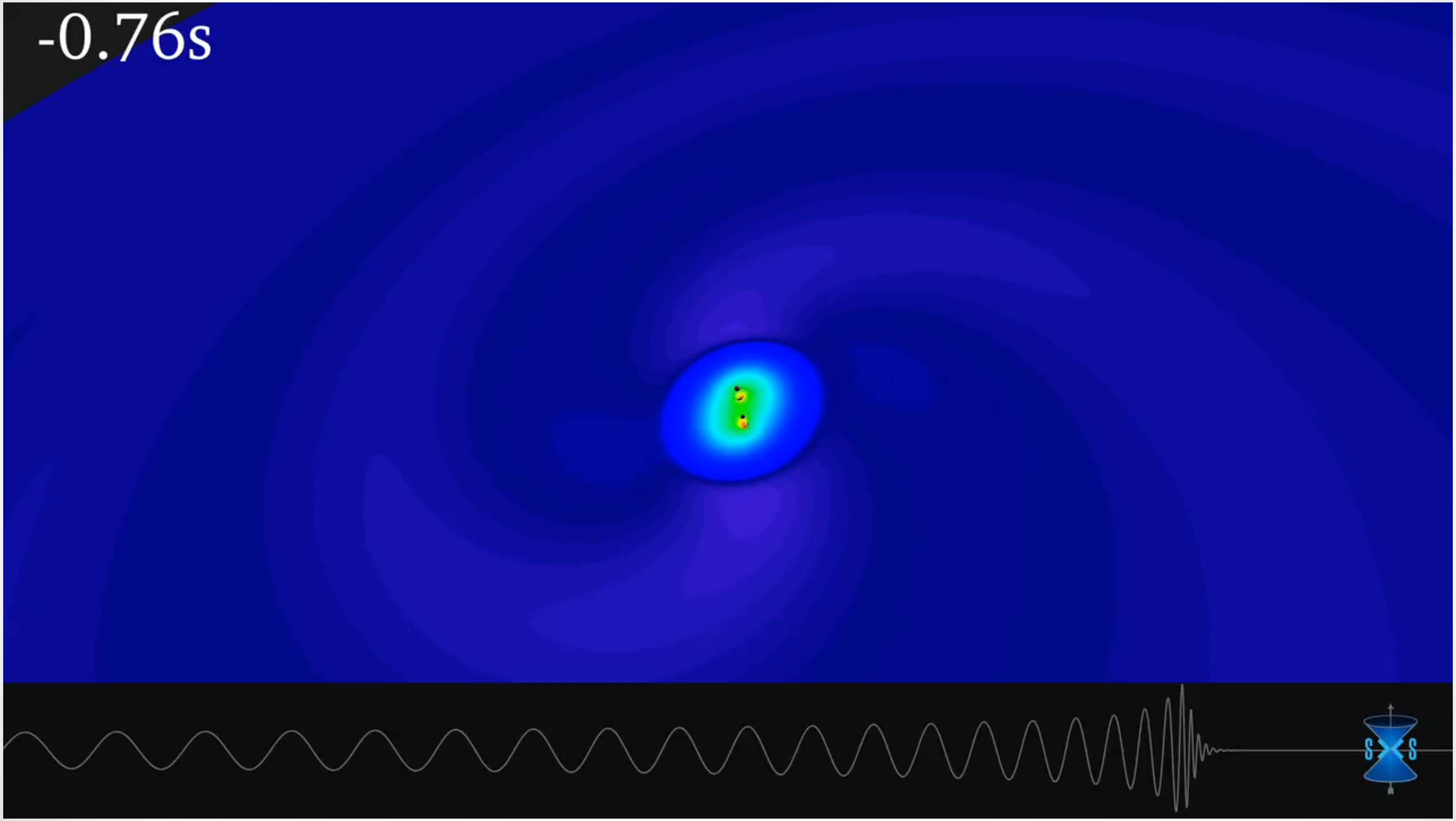
We are opening new ways to observe the Universe and its densest parts
We will also be able to test GR in new regimes

Time around 2020 will be very interesting for transient sky and tests for gravitation !

Abbott et al, arXiv 1606.04856

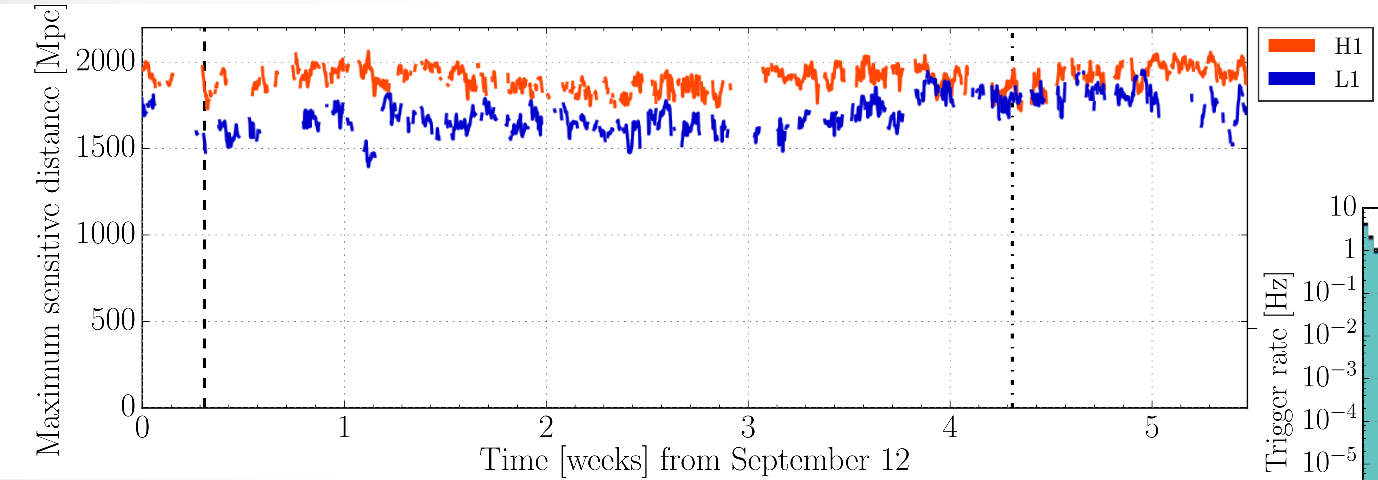


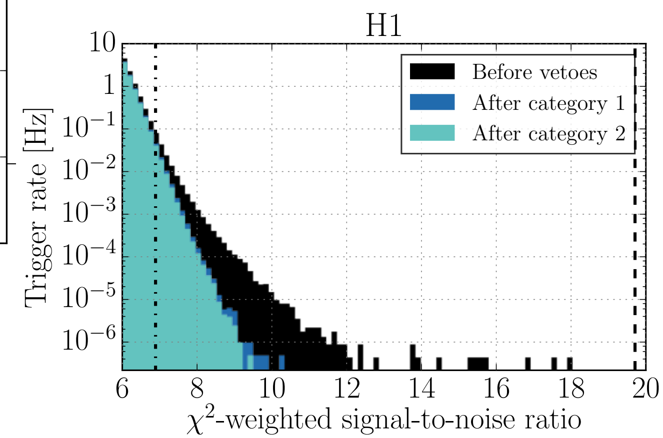
backup


-0.76s

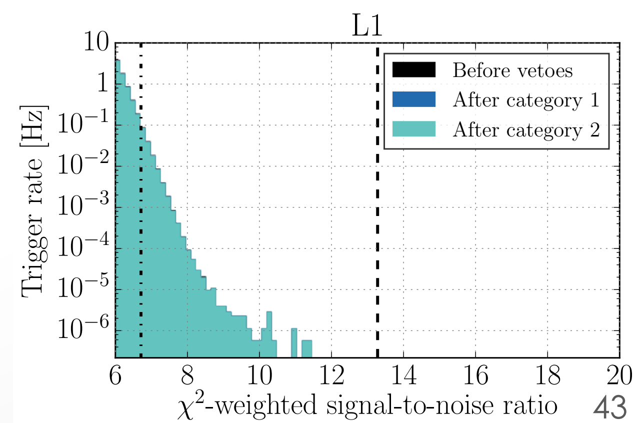
Checks on data quality

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





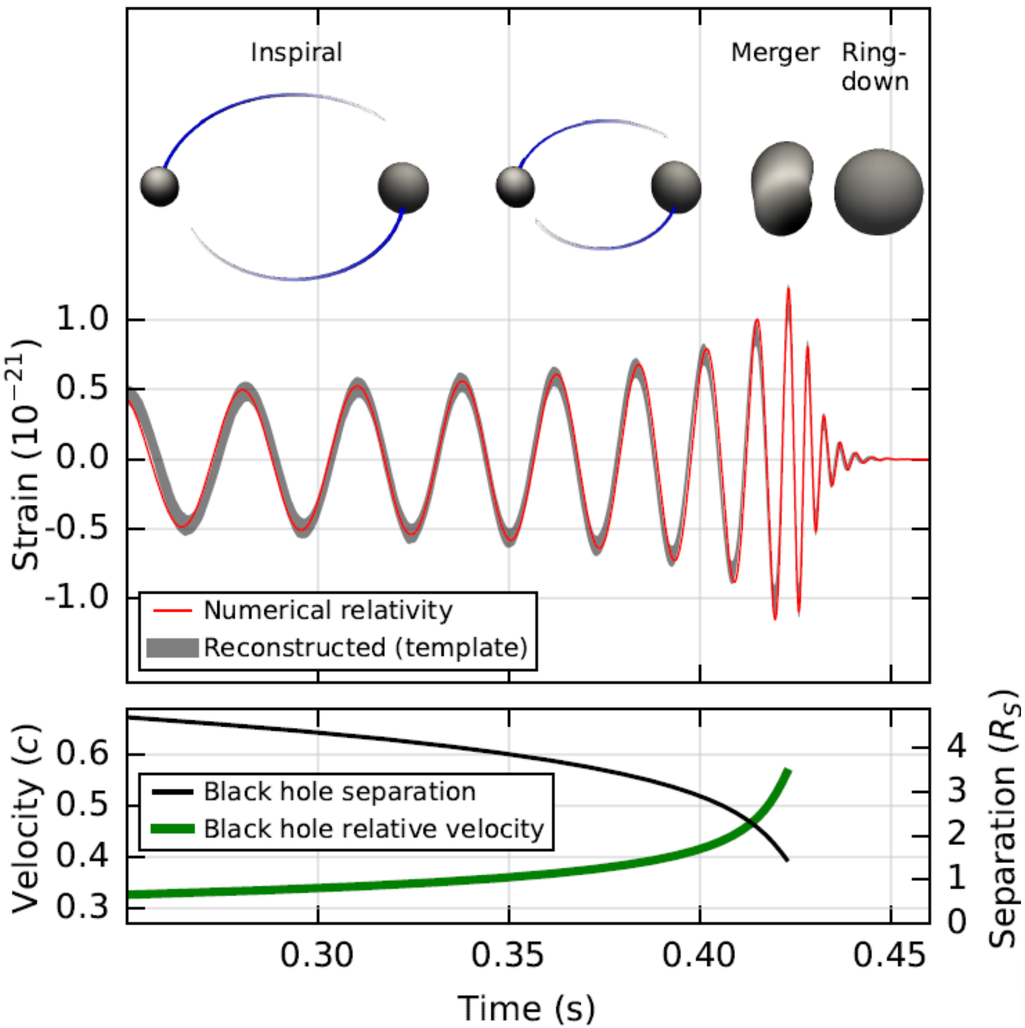
- Periods removed
  H1 ~5 % - L1 ~0.1 %



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

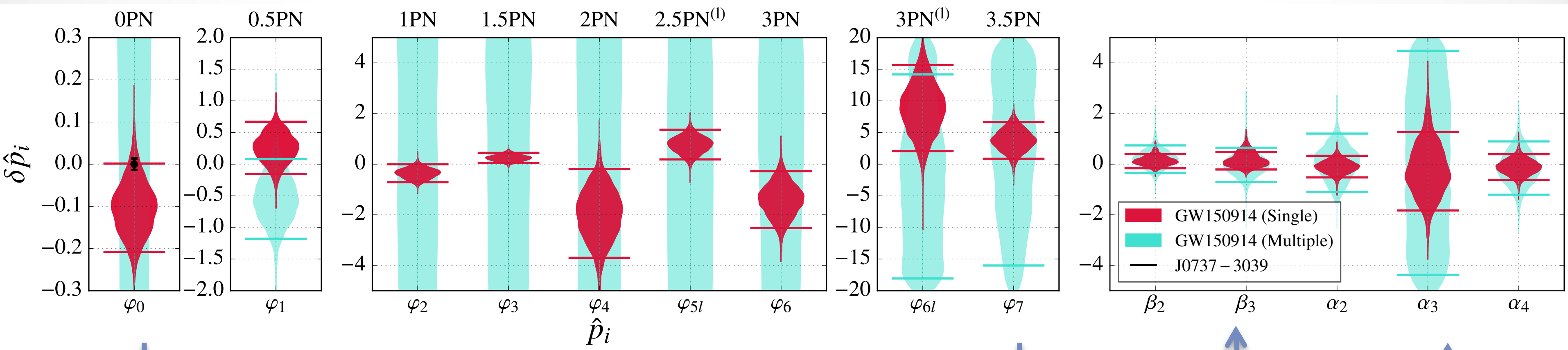
Abbott et al, Living Reviews in Relativity 19, 1

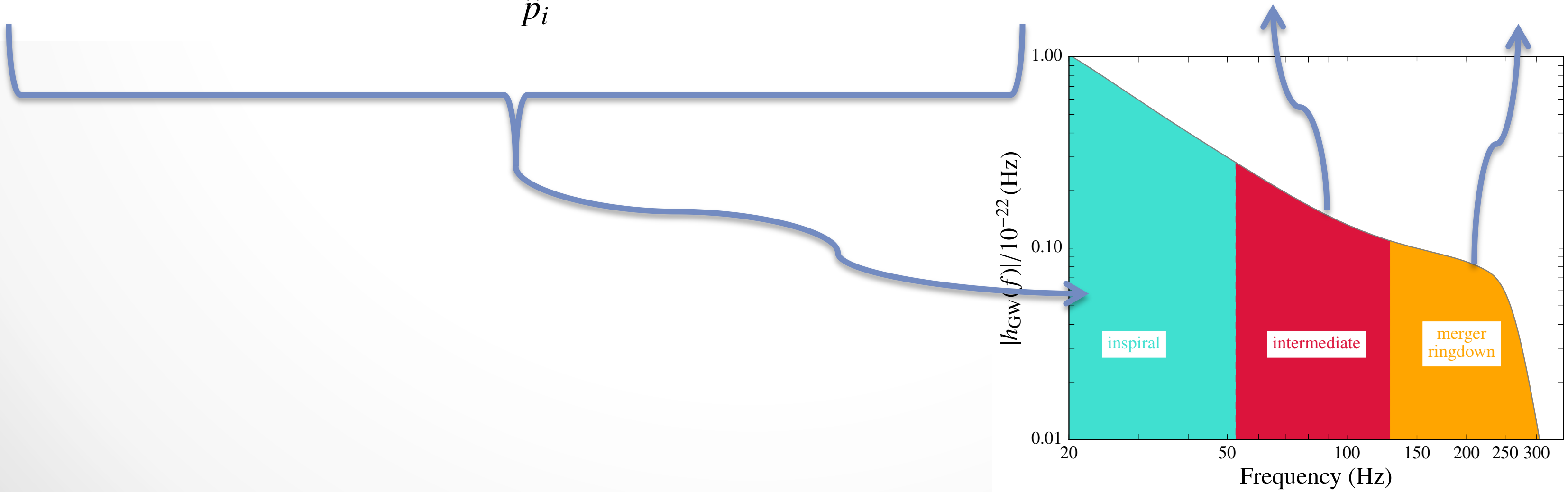


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
4
3
2
1
0
Separation (R_S)
0.30
0.35
0.40
0.45
Time (s)

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*** $\Rightarrow$ $\dddot{Q} \approx a\, M\, R^2 \;/\; T^3$

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~Rs
- Relativist : v ~ c
- asymmetric

Neutron star (NS)
Black hole (BH)