Introduction of gravitational wave detection: scientific case and methods

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EIROForum School on Instrumentation

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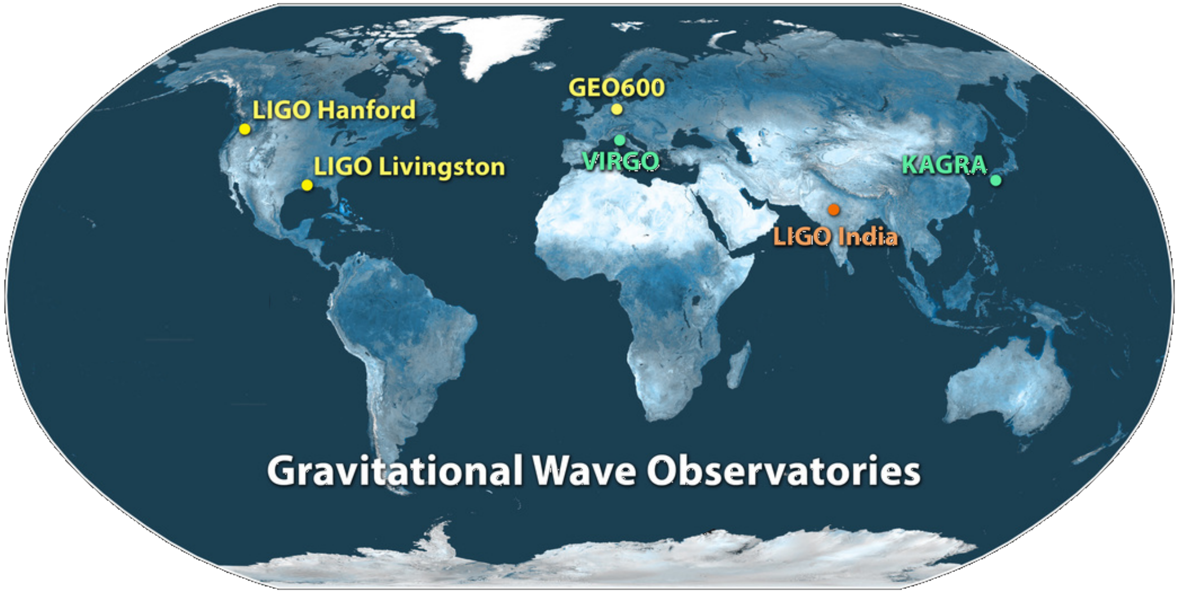
Detections of gravitational waves

By the network of interferometric detectors
Advanced LIGO – Advanced Virgo

Detectors: LIGO Hanford (H1) and LIGO Livingston (L1)
Data analysis: LSC (LIGO Scientific Collaboration) + Virgo

LSC : ~900 members
~80 institutions
from ~15 countries

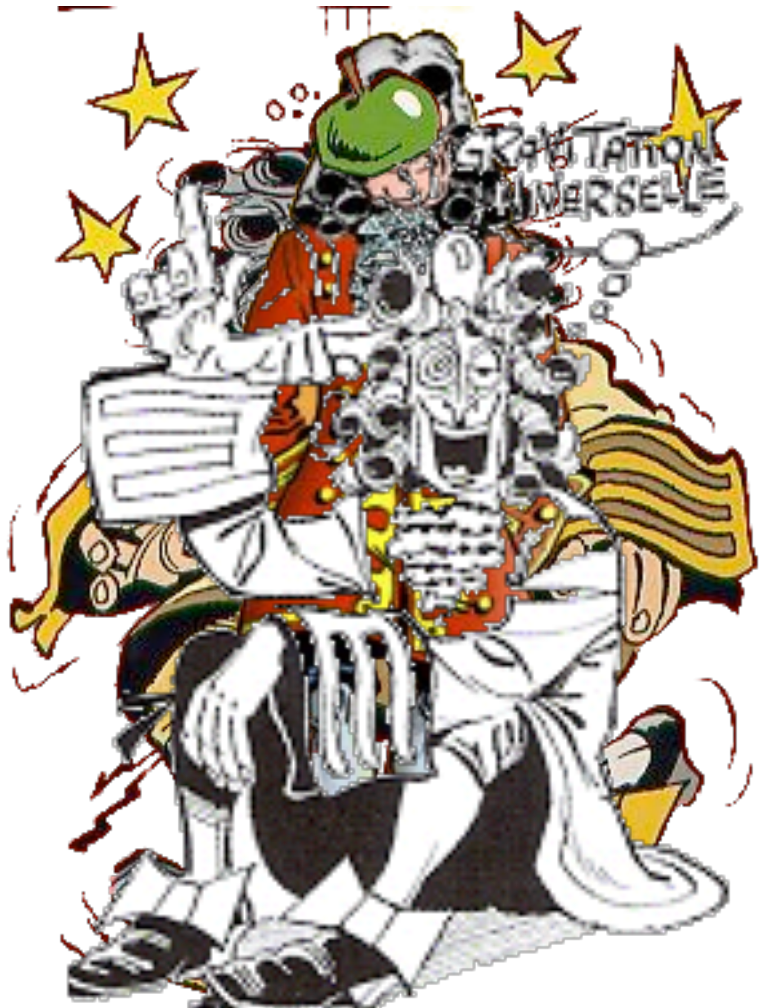
Virgo : ~200 members
19 laboratories
from 5 countries



Since 2007, LVC = LIGO-Virgo Collaboration

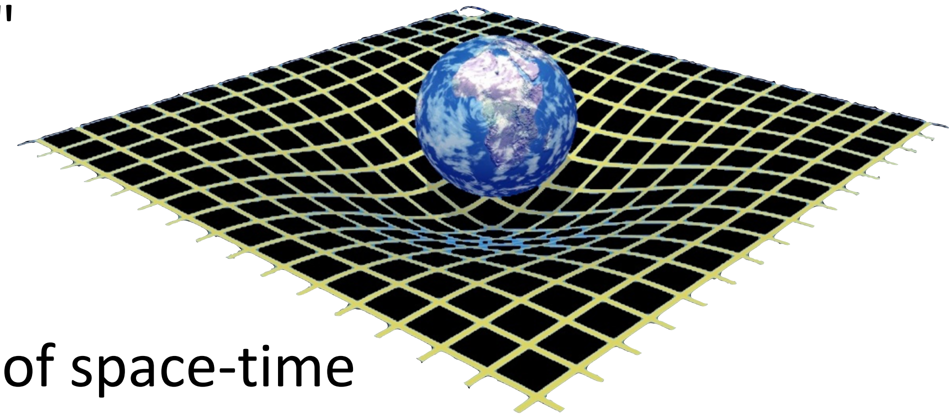
How does it work ?

- Main ingredient : gravity

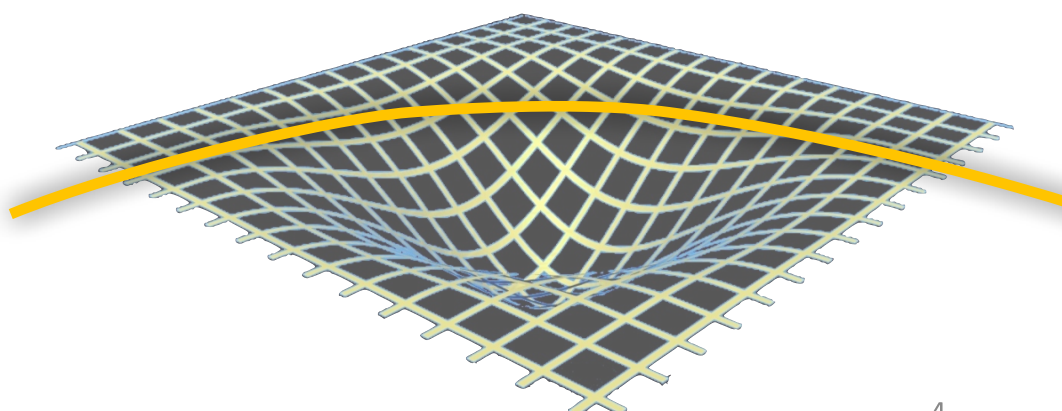


The work of gravity

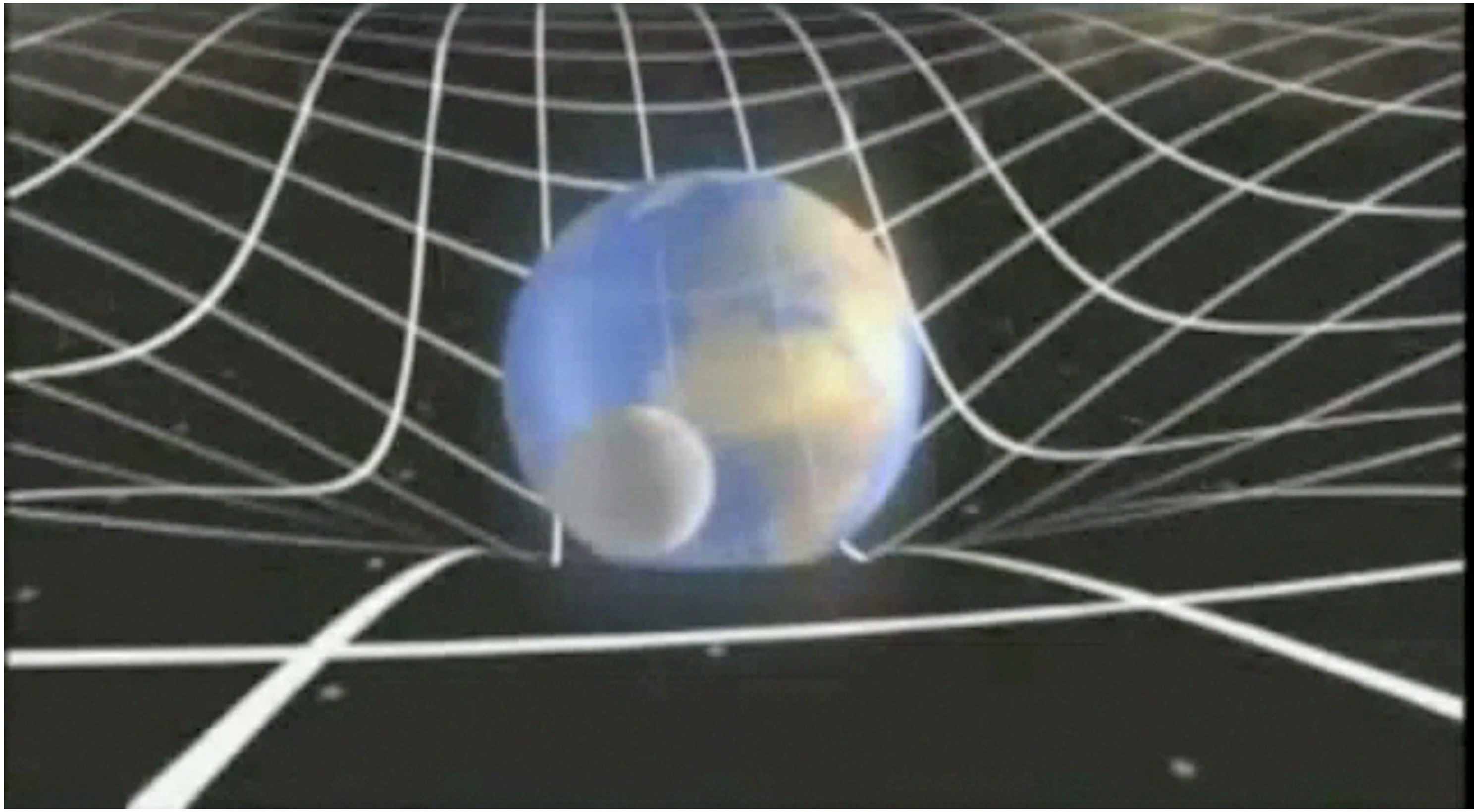
- Theory of General Relativity (GR)
- Einstein 1915-1918 : geometric theory of gravitation
- A mass "bends" and "deforms" space-time



- The trajectory of a mass is influenced by the curvature of space-time



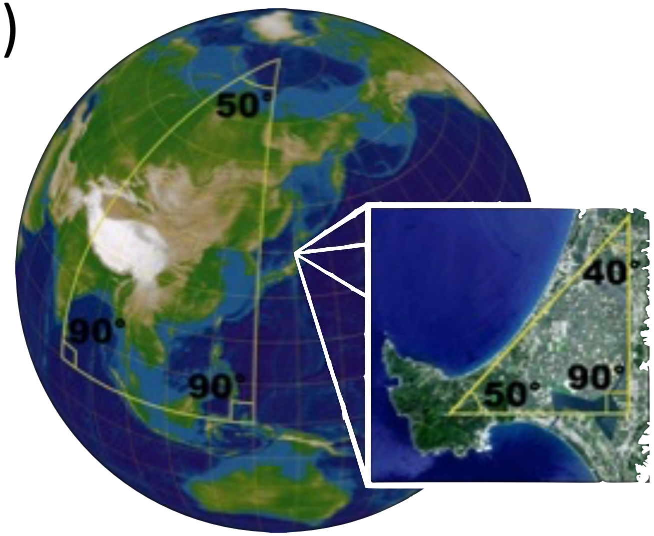
The work of gravity



- But this is only a picture !
- Space-time is not an elastic surface in 2 dimensions !
- Very difficult to represent in 3 (rather 4) dimensions

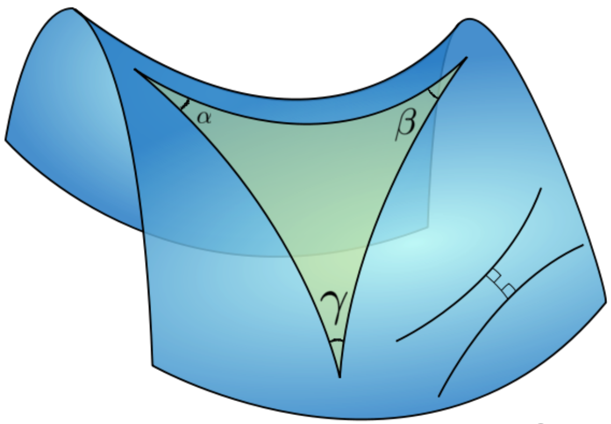
« Curved » space-time

- What is a curved space ? (= "manifold")
  - examples : sphere, saddle
- Can we measure curvature ?
  - we cannot see our space from "outside"
  - but we can measure angles
  - the sum of the angles of a triangle is not always equal to π !
- positive curvature



$$\sum \text{angles} = \alpha + \beta + \gamma > \pi$$

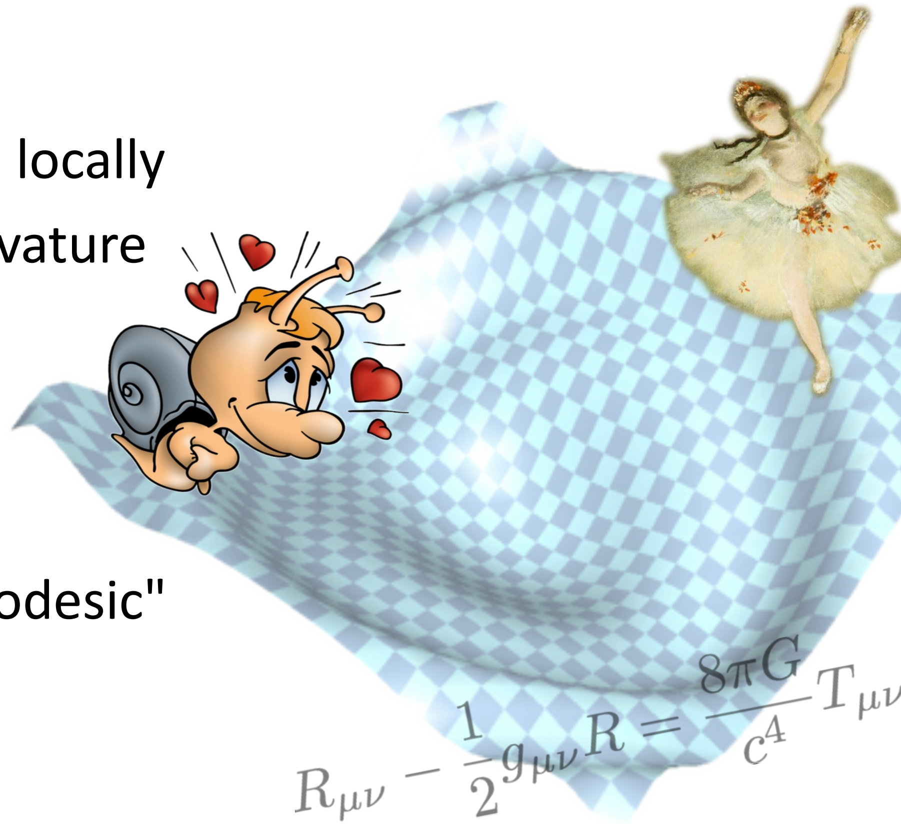
- negative curvature



$$\sum \text{angles} = \alpha + \beta + \gamma < \pi$$

Curvature of space-time

- Newton : space is Euclidian (flat) and time is universal
  - flat space-time !
- General Relativity
  - space is curved and time is defined locally
  - one cannot go "out" to see the curvature
    - "intrinsically" curved space
    - intrinsic curvature
  - go straight (free fall) = follow a "geodesic"
  - note that the time is also curved !
  - as a first approximation, finds
    the results (trajectories) of newtonian mechanics



The metric

- In space-time, measure
  - the distance between two points
  - the angle between two vectors
- Measure of the distance between two infinitesimally close events in spacetime
- Need a "metric", start from the "line element" seen in special relativity :

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

with c = 1

- Which can be written $ds^2 = \eta_{\alpha\beta} dx^\alpha dx^\beta$

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad dx^0 = dt, \quad dx^1 = dx, \quad dx^2 = dy, \quad dx^3 = dz$$

- $\eta_{\mu\nu}$ is the metric of a flat spacetime,
  - Minkowski spacetime, used in special relativity

The metric

- But the space is not flat !
- The metric can be general : $g_{\mu\nu}$

- It contains all information about spacetime curvature
  - It is a « rank 2 tensor »

- The curvature is also defined by another tensor, which depends on $g_{\mu\nu}$
  - the Ricci tensor $R_{\mu\nu}$

- **But what generates the curvature of spacetime ?**

The Einstein field equations

- Answer : the energy-momentum content of spacetime !
  - this includes mass
- Einstein Field Equations :

still c = 1 !
would be $\frac{8\pi G}{c^4}$.

$$\underbrace{\left(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R\right)}_{\text{curvature term}} = 8\pi G \underbrace{\left(T_{\mu\nu}\right)}_{\text{energy-momentum term}}$$

- Energy-momentum bends spacetime
  - being far from some energy density doesn't mean there is no bending !
- Spacetime tells mass (energy momentum) how to move
- These equations are non-linear

Gravitational waves

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für

Gravitational waves

- Flat space-time = Minkowski metric
  - Add a perturbation to a flat metric $h_{\mu\nu}$
  - Linearize Einstein Field Equations
  - Choose a coordinate system ("Transverse Traceless" (T T) gauge)
- Obtain a wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

(in vacuum)

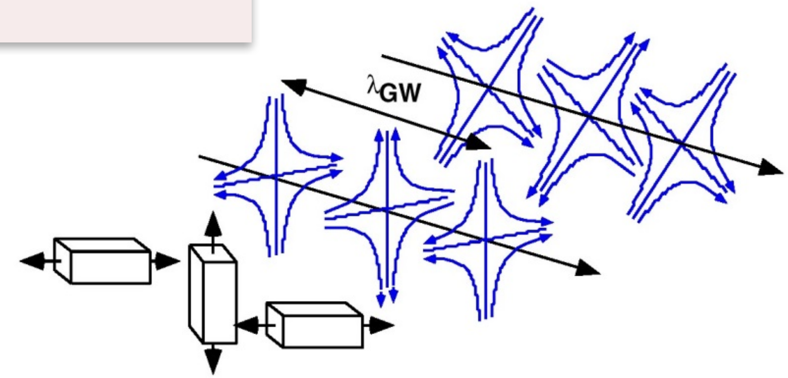
- Solution (in vacuum) :

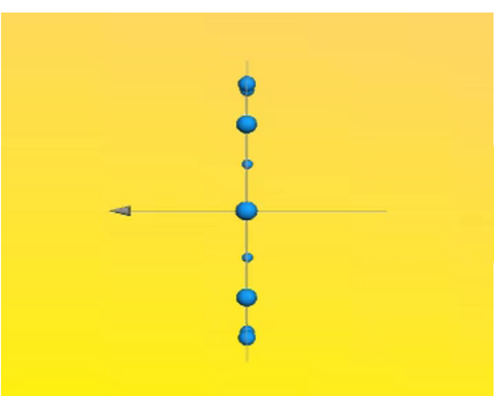
$$h_{\mu\nu} = A_{\mu\nu} \cdot e^{-i(\vec{k}\cdot\vec{x}-\omega\cdot t)}$$

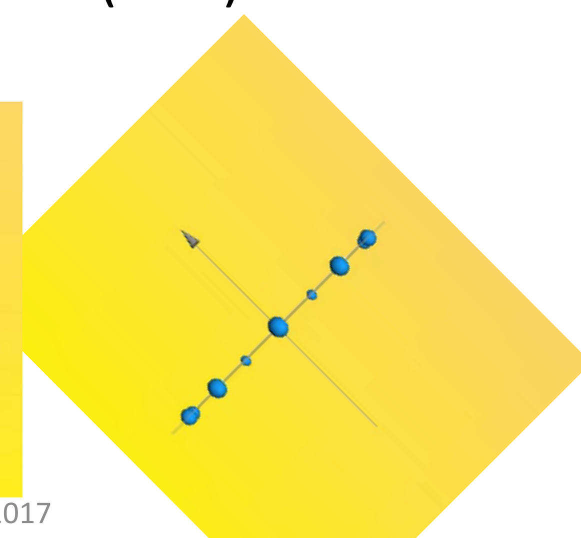
Gravitational waves

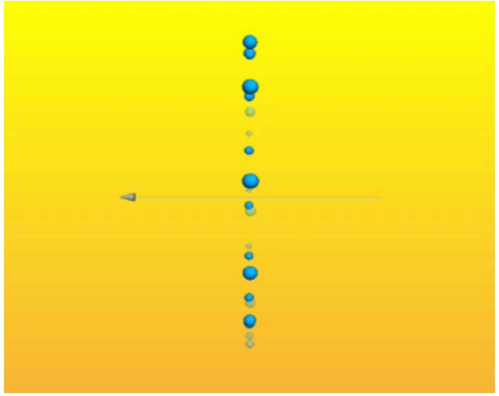
$$h_{\mu\nu} = A_{\mu\nu} \cdot e^{-i(\vec{k}\cdot\vec{x} - \omega \cdot t)}$$

- In vacuum
  - Plane wave
  - Speed = c (speed of light)
- 2 polarizations
  - Rotated by 45° one vs the other
- Effect on a set of (free) “test” masses





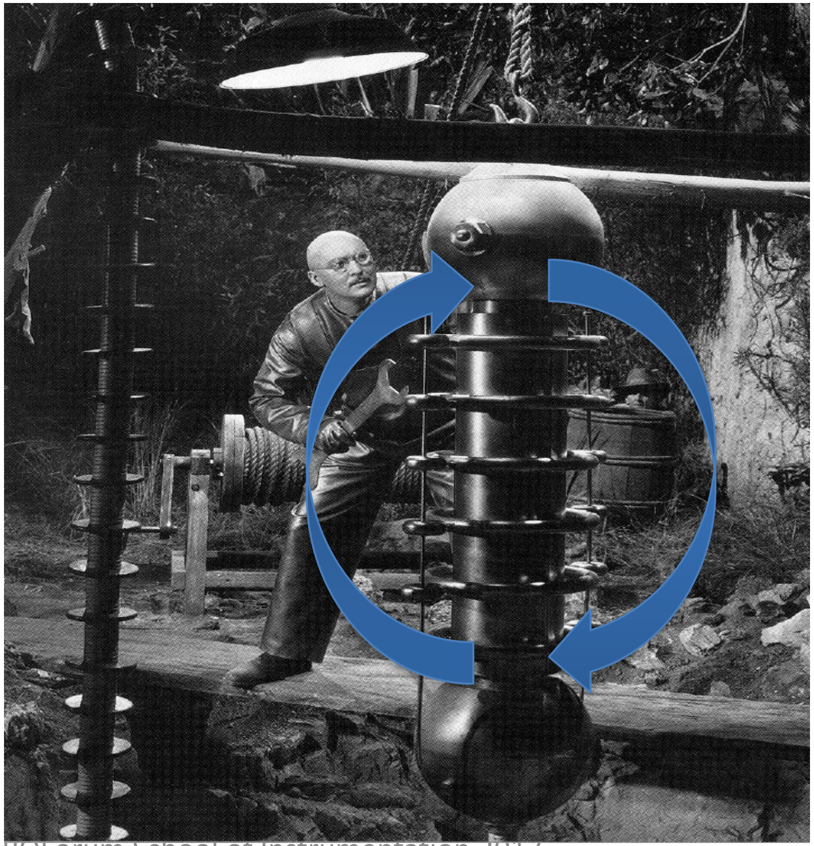




$$h_{\mu\nu} = h_{+}(t - z/c) + h_{x}(t - z/c)$$

Gravitational waves

- Production :
  - Distribution of masses : acceleration of quadrupolar moment



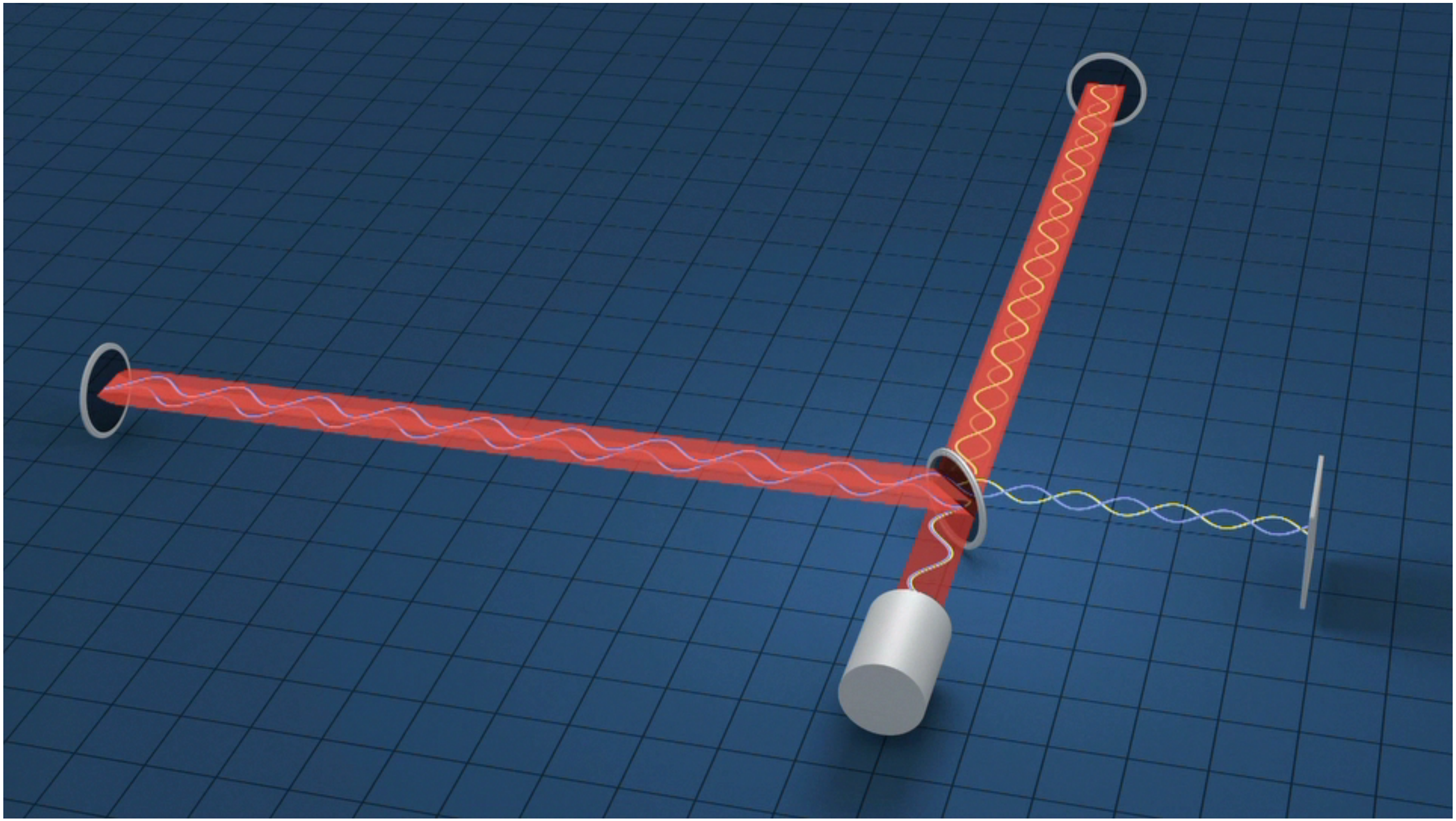
$$h \approx 32\pi^2 \cdot \frac{G}{c^4} \cdot \frac{1}{r} \cdot M \cdot R^2 \cdot f_{orb}^2$$

- Examples
  - M = 1000 kg, R = 1 m, f = 1 kHz, r = 300 m

    $h \sim 10^{-35}$
  - $M = 1.4\ M_{\odot}$, R = 20 km, f = 400 Hz, $r = 10^{23}$ m (15 Mpc = 48,9 Mlyr)

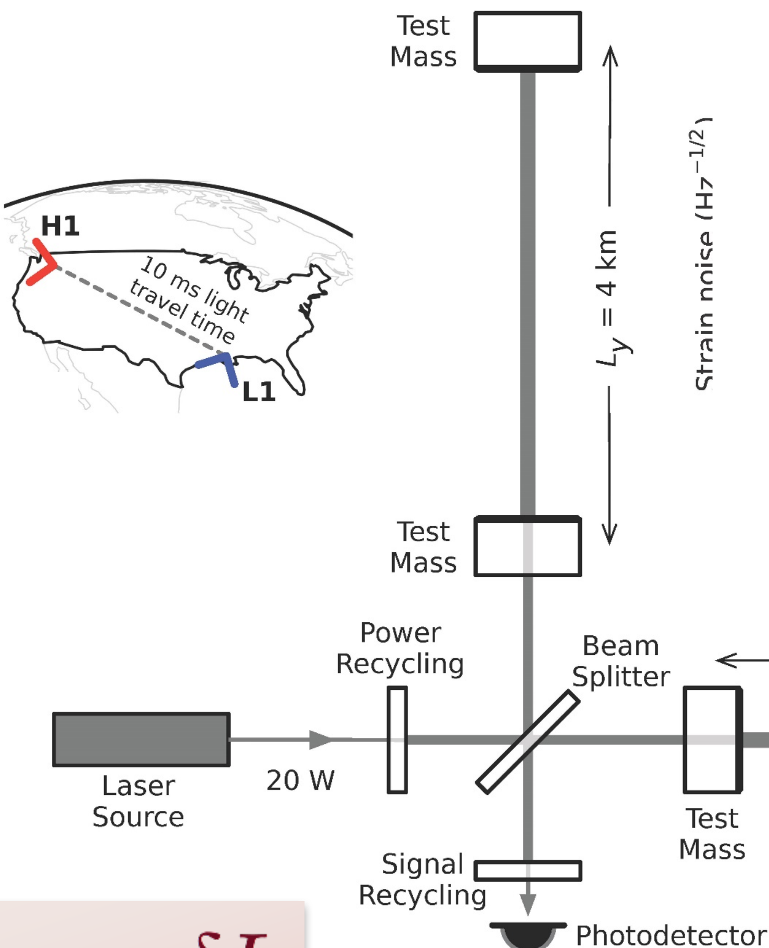
    $h \sim 10^{-21}$

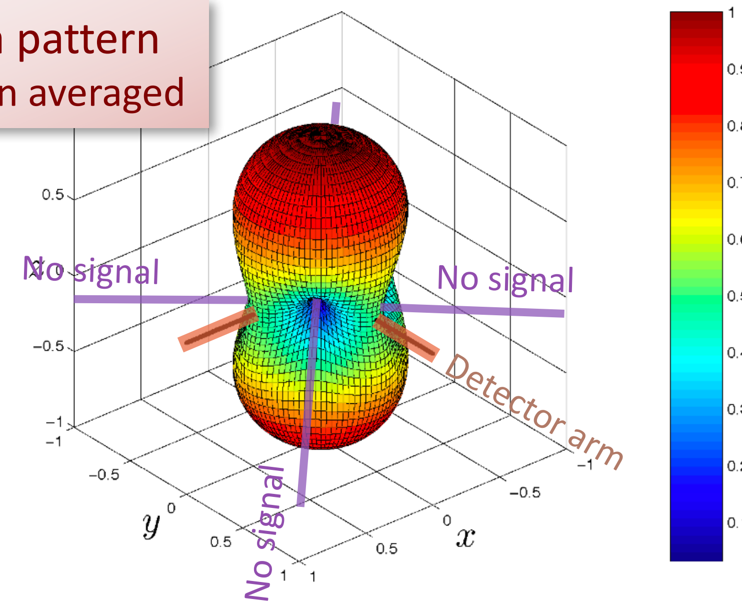
Michelson interferometer : a gravitational waves “sensor”



LIGO and Virgo Collaborations

Michelson interferometer : a gravitational waves "sensor"



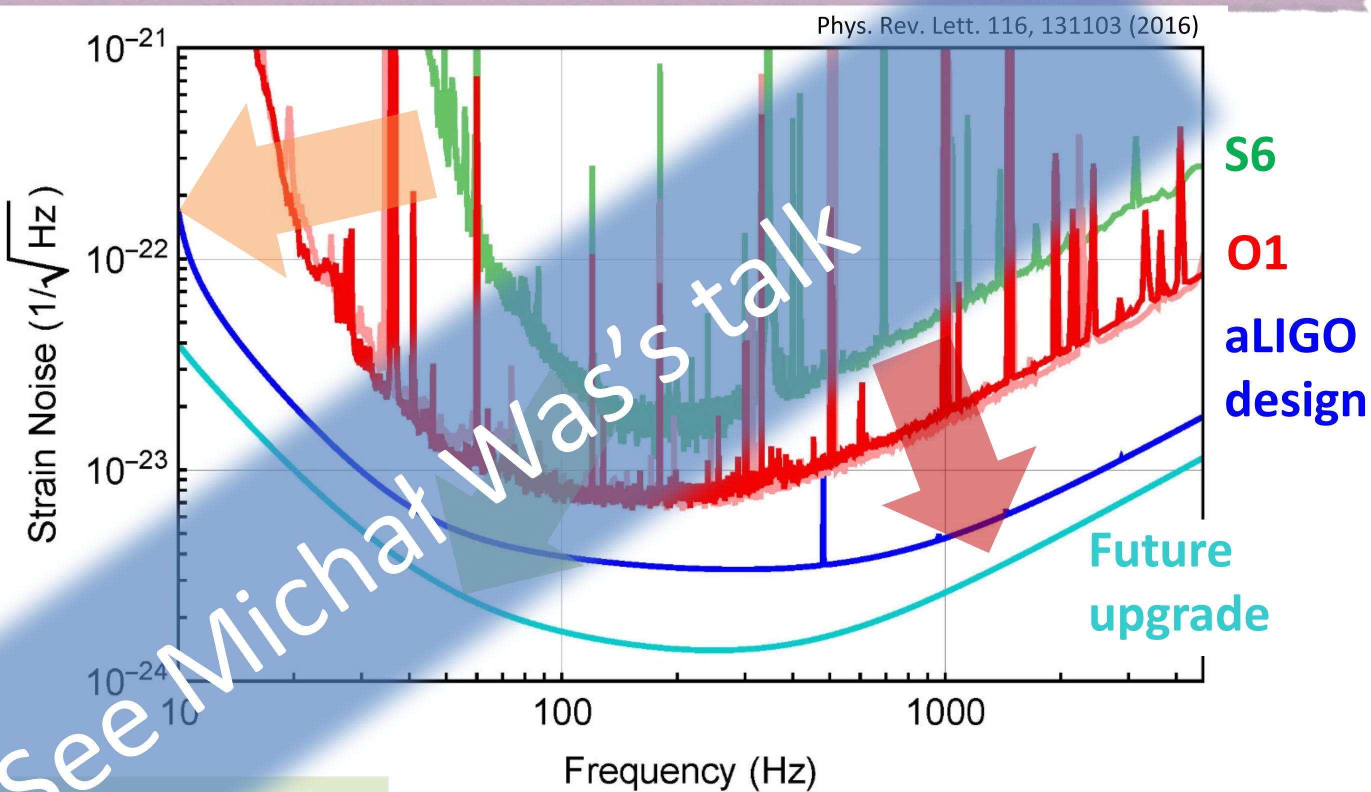


$$h = 2\frac{\delta L}{L}$$

$$h \approx 10^{-21} \quad \Rightarrow \quad \delta L \approx 10^{-18}\ \mathrm{m}$$

Sensitivity

Seismic noise
Improved seismic isolation



Thermal noise
Monolithic suspensions
Improved mirror coatings
Larger beam size

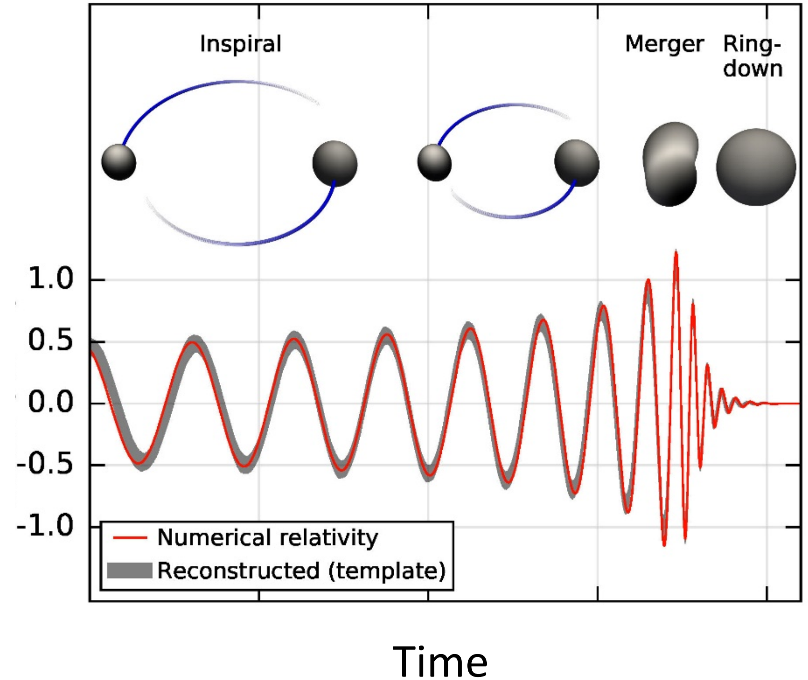
Quantum noise
Higher laser power
Thermal compensation
Signal recycling
DC detection

Searching for the coalescence of a binary system of compact objects (CBC)

- Target: Signals from the coalescence of a binary system of compact objects
  - Neutron stars (BNS), Neutron Star + Black Hole (NS-BH), Binary Black Hole (BBH)
- Phases of the coalescence:
  - Inspiral
    - Masses m_1 and m_2 orbiting around each other
    - Emitting GW
      - Frequency ↗ , amplitude ↗
    - Waveform characterized by « chirp mass »

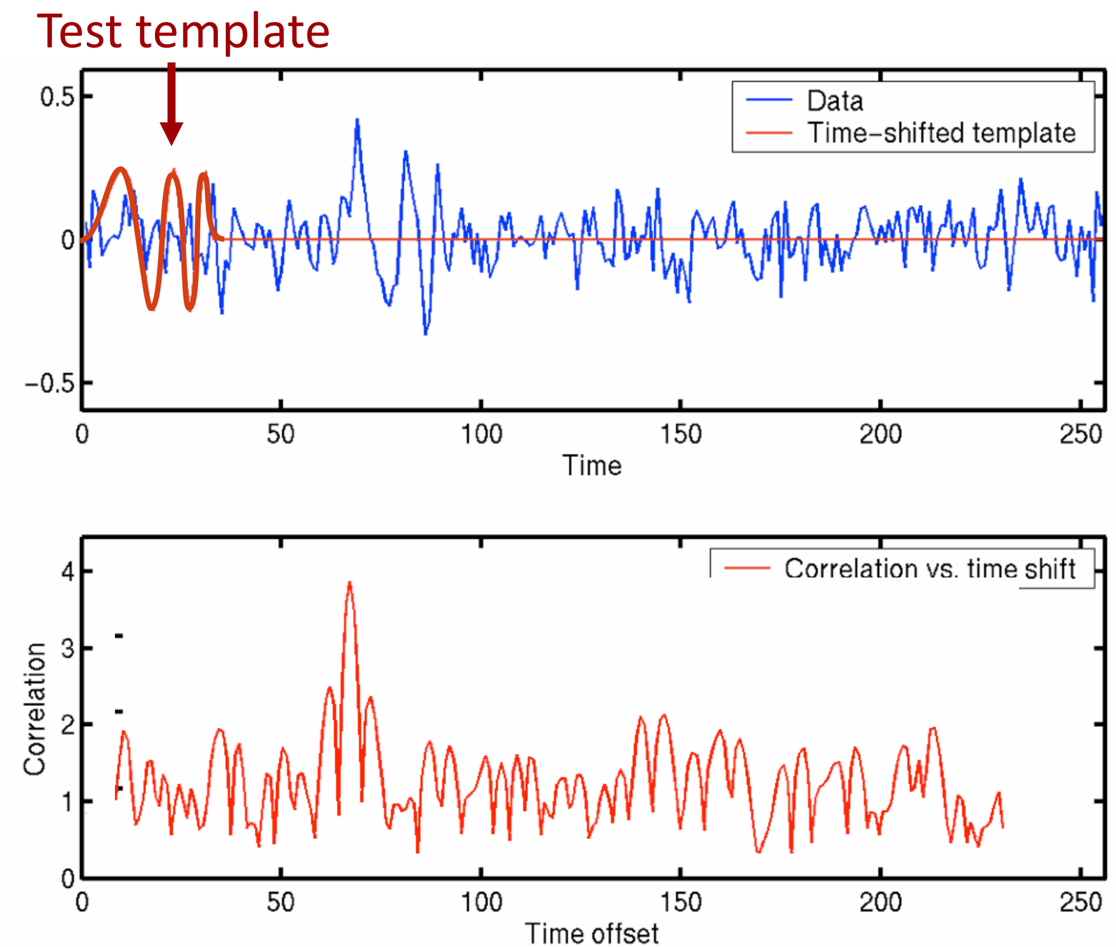
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

  - Merger : numerical relativity computation
  - Ringdown : decompose in quasi-normal modes



Searching for the coalescence of a binary system of compact objects (CBC)

- Modelled search : analysis principle
  - Production of a bank of templates (theoretical waveforms)
  - Matched filtering = weighted cross correlation signal/template



Searching for the coalescence of a binary system of compact objects (CBC)

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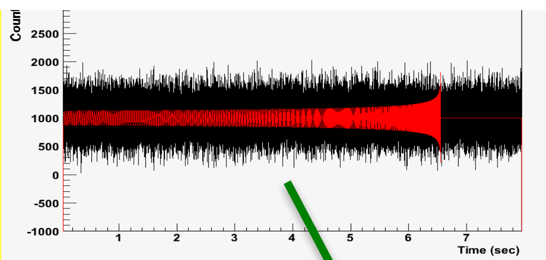
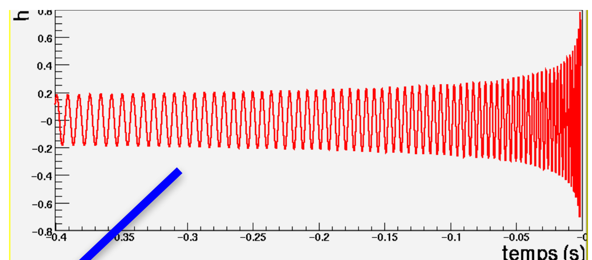
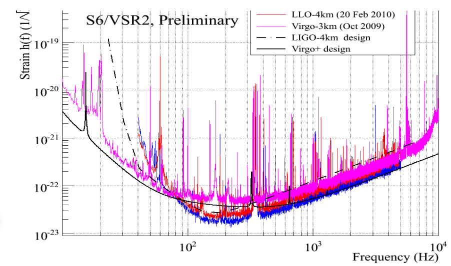
Signal embedded in the noise



Template

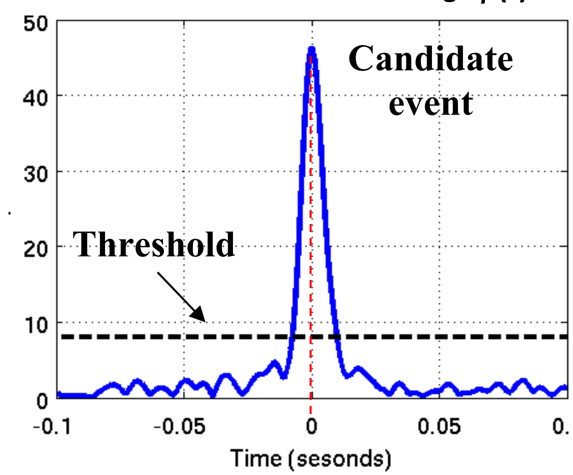


Detectors noise spectral density



$$\langle \tilde{a}, \widetilde{T} \rangle = 2\left[\int_0^\infty \frac{\tilde{a}(f).\widetilde{T}^*(f)}{S_n(f)} \mathrm{d}f + \mathrm{c.c.}\right]$$

Result of the matched filtering : ρ(t)

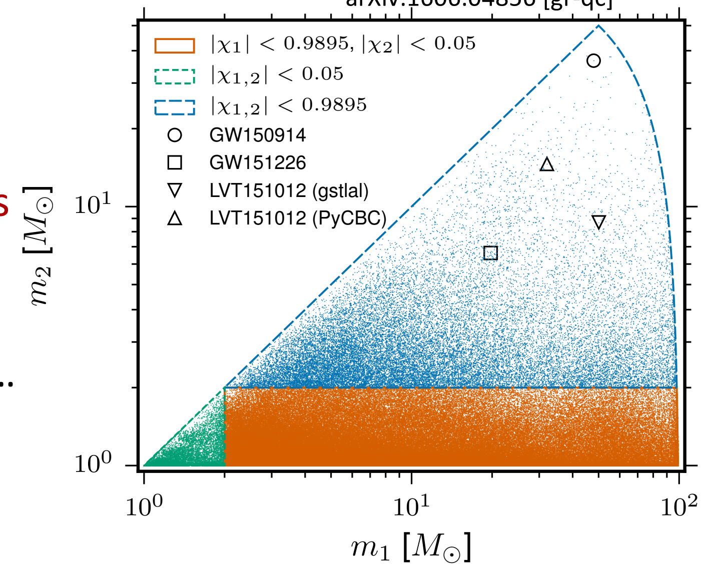


- Very sensitive to phase evolution

Searching for the coalescence of a binary system of compact objects (CBC)

- **Intrinsic parameters**
  - masses, spins (aligned) drive
    - the system dynamics
    - the waveform evolution
  - 4-D parameter space scanned with ~250,000 templates

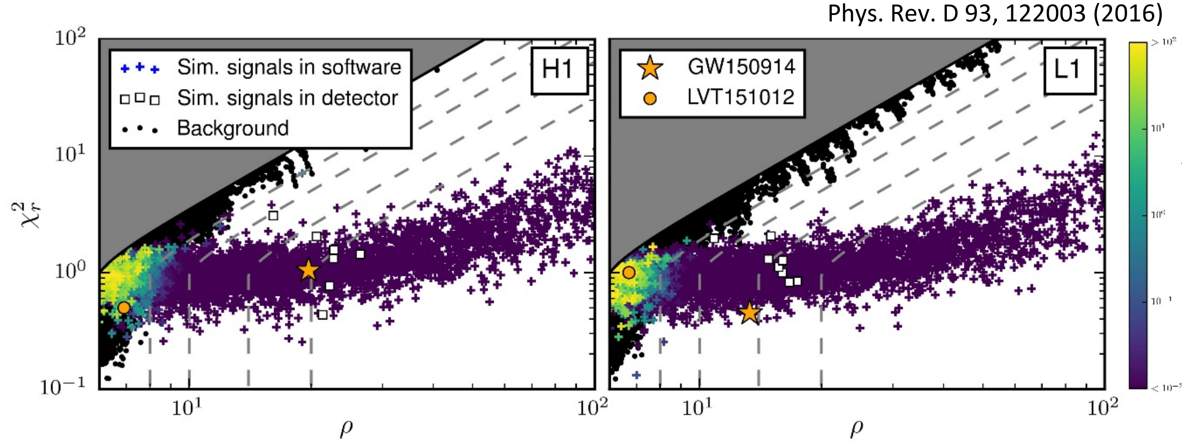
arXiv:1606.04856 [gr-qc]



- **Extrinsic parameters**
  - Position in the sky, orientation of the binary, initial phase,… impact
    - Arrival time of the signal
    - Global amplitude and phase
  - Maximized over

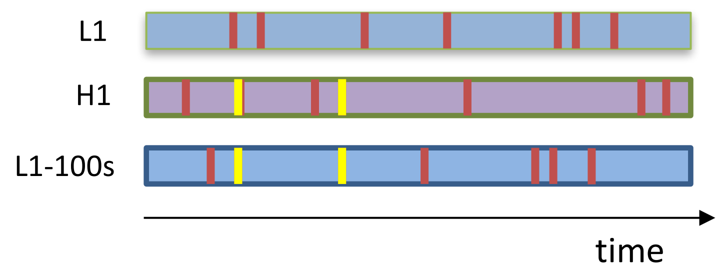
- Test consistency of the signal with the template
- Extract triggers coincident in both detectors
- Apply data quality vetoes

Phys. Rev. D 93, 122003 (2016)



False alarm rate

- False alarm rate
  - Measured from background estimated on data
  - Time shifts by N x 0.1 s between H1 and L1



  - Case of GW150914, first analysis for February annoucement
    - $N_{max} = 10^7$ shifts, T_{bkgd} = 200,000 yrs
    - GW150914 louder than all background ➔ lower limit on significance

- Importance of vetoing environmental transient disturbances.
  - Monitoring by array of sensors
  - ~10^5 channels for each detector

Seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, AC-power line monitors, cosmic ray detector

Introducing...

- O1 run
  - September 12, 2015 – January 12, 2016
    - H1 = LIGO Hanford, L1 = LIGO Livingston

- GW150914
  - Detected September 14, 2015 at 09:50:45 UTC
  - Masses : 29 and 36 solar masses
  - Duration : 0.2 s

- LVT151012, candidate
  - on October 12, 2015 at 09:54:43 UTC

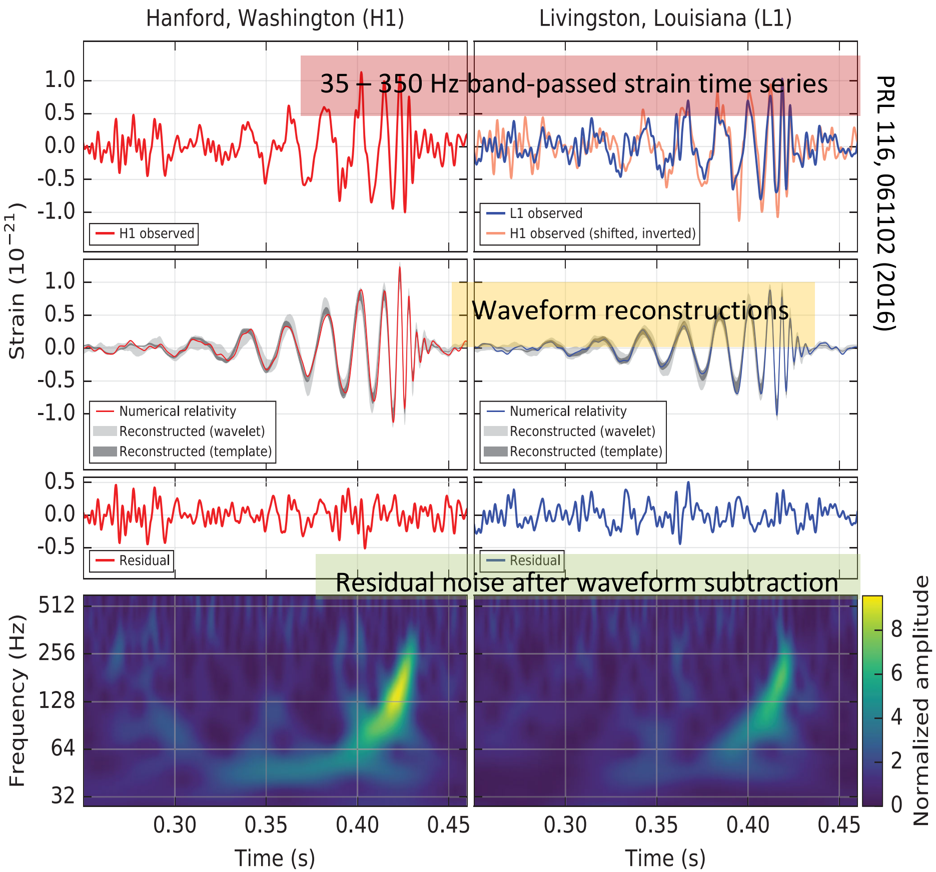
- GW151226
  - Detected December 26, 2015 at 03:38:53 UTC
  - Masses : 7 and 14 solar masses
  - Duration : 1 s

- O2 run
  - Since December 2017, still running

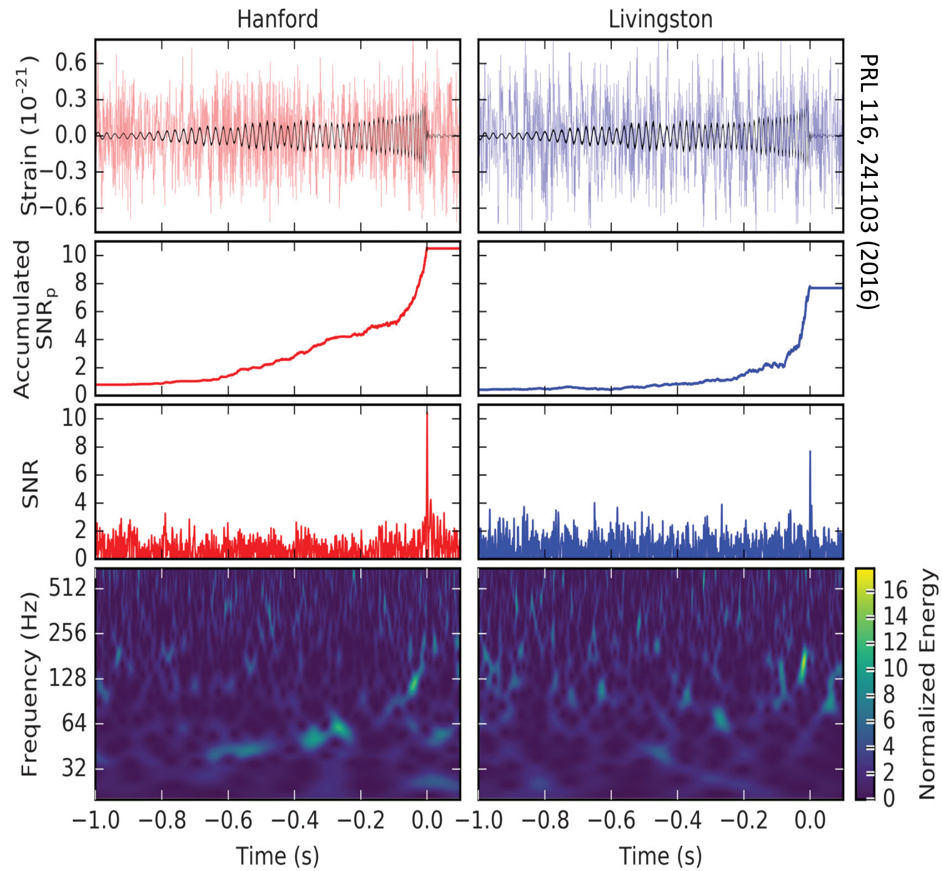
- GW170104
  - Detected January 04, 2017 at 10:11:59 UTC
  - Masses : 31 and 19 solar masses
  - Duration : 0.2 s

Naked eye view of some events

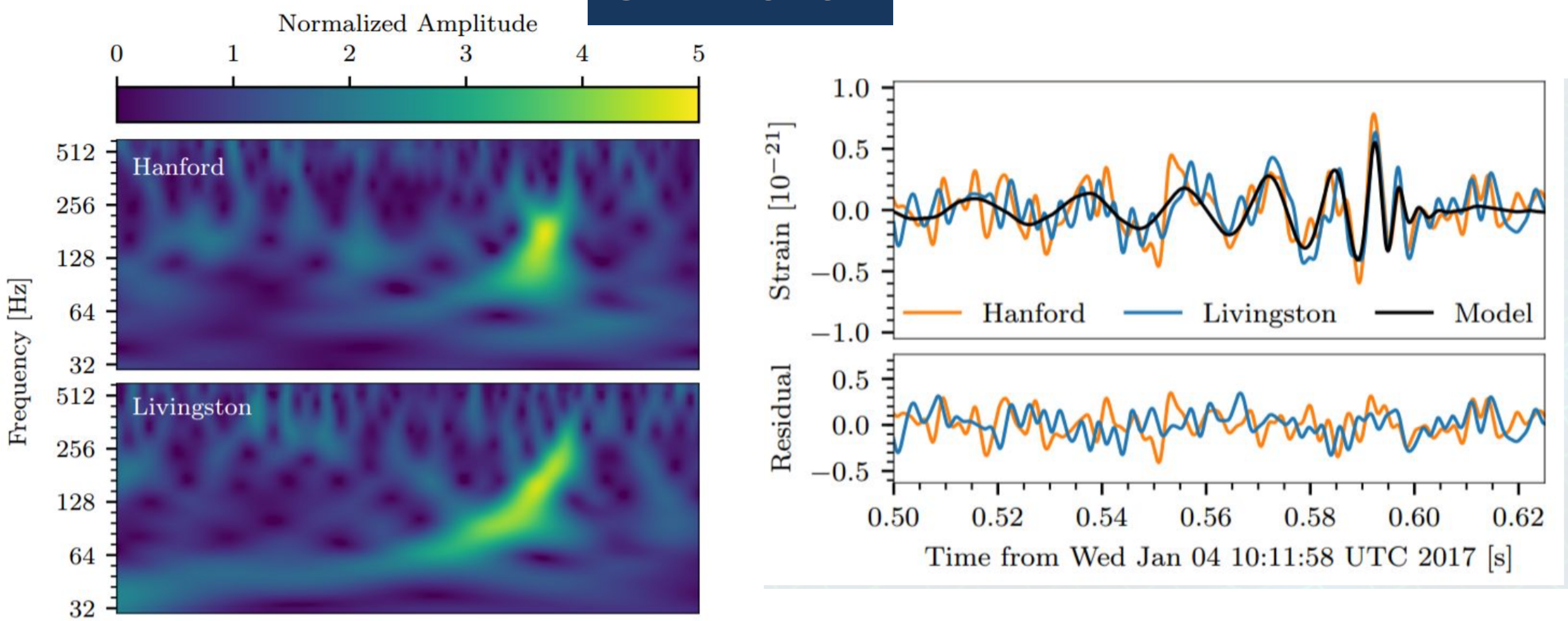
GW150914



GW151226

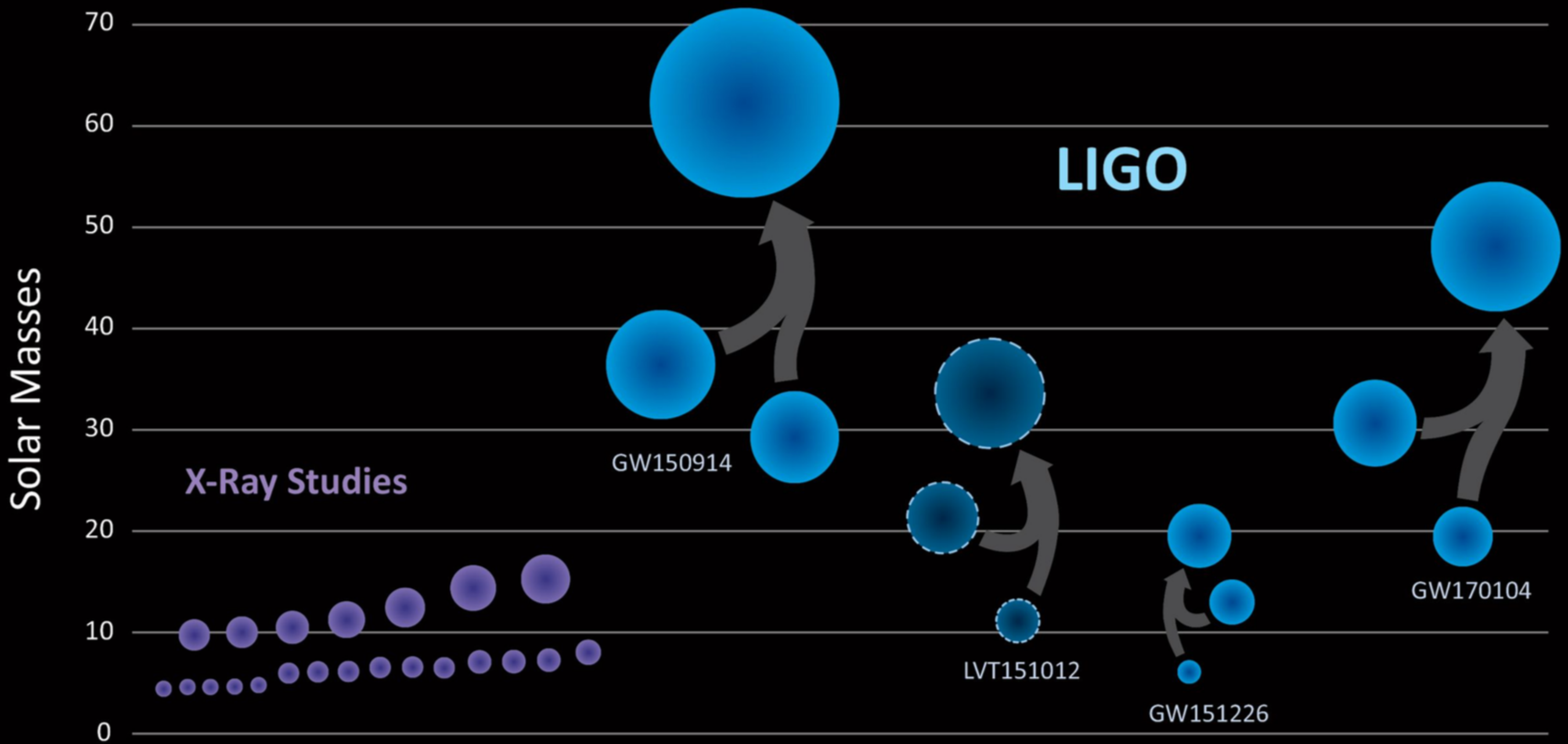


GW170104



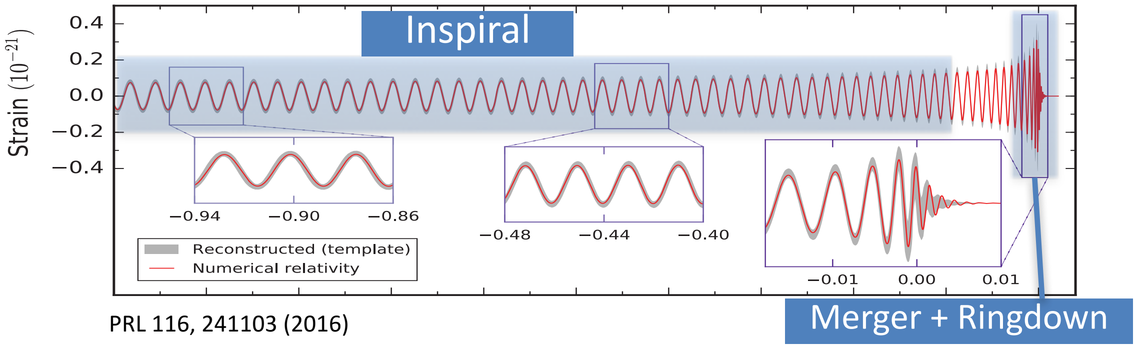
- For all events :
- Waveform reconstructed
  - Coherent signal in both detectors
  - Agreement with best-fit theoretical waveforms (waveforms from perturbative theory + NR = Numerical Relativity)
- Residual noise consistent with instrumental noise

Black Holes of Known Mass



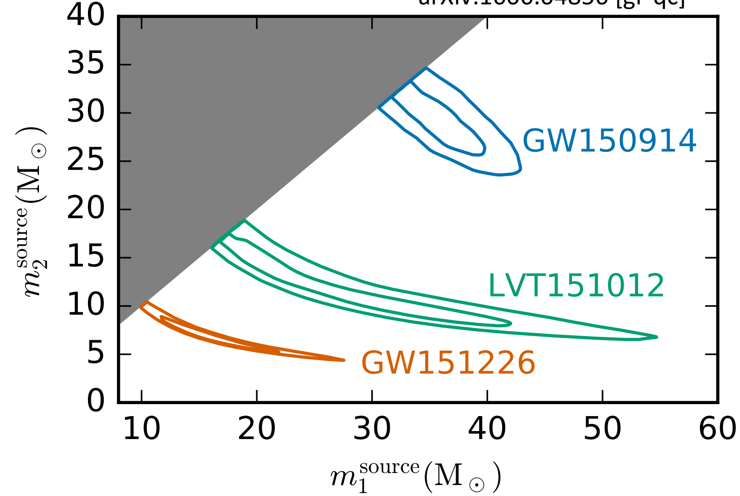
Credit LIGO

Intrinsic Parameters



PRL 116, 241103 (2016)

arXiv:1606.04856 [gr-qc]



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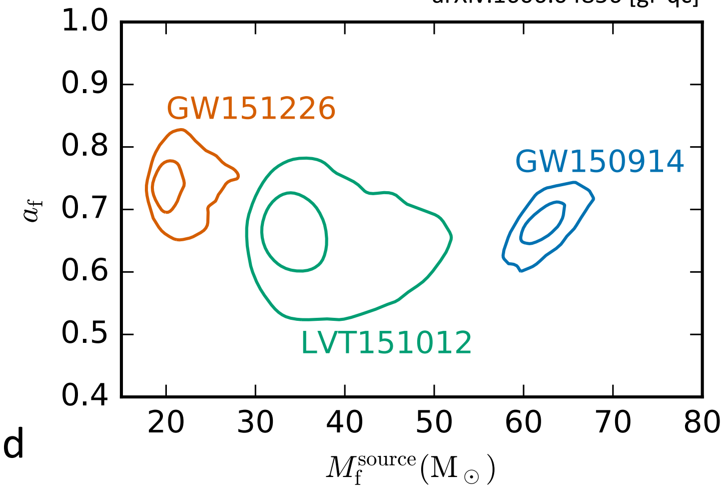


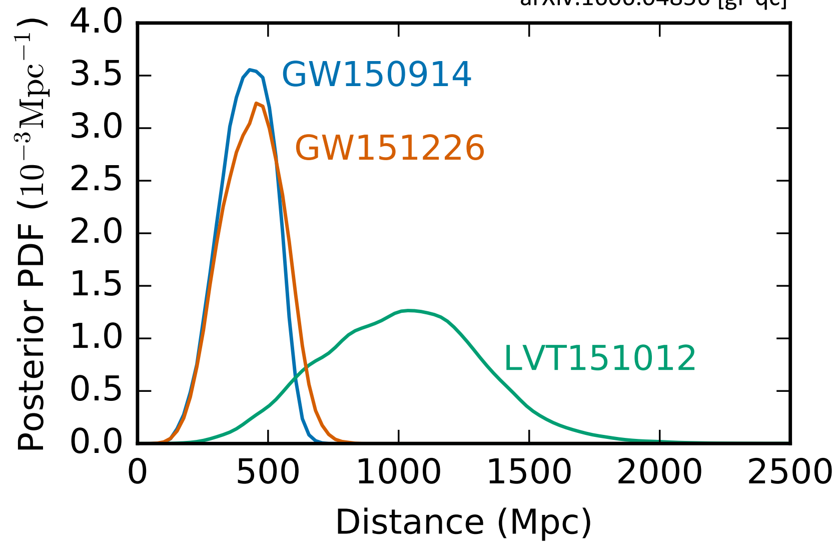
- Encoded in GW signal :
  - ***Inspiral***
    - chirp mass, mass ratio, spin components
    - Additional spin effect
      - If not // orbital angular momentum: orbital plane precession

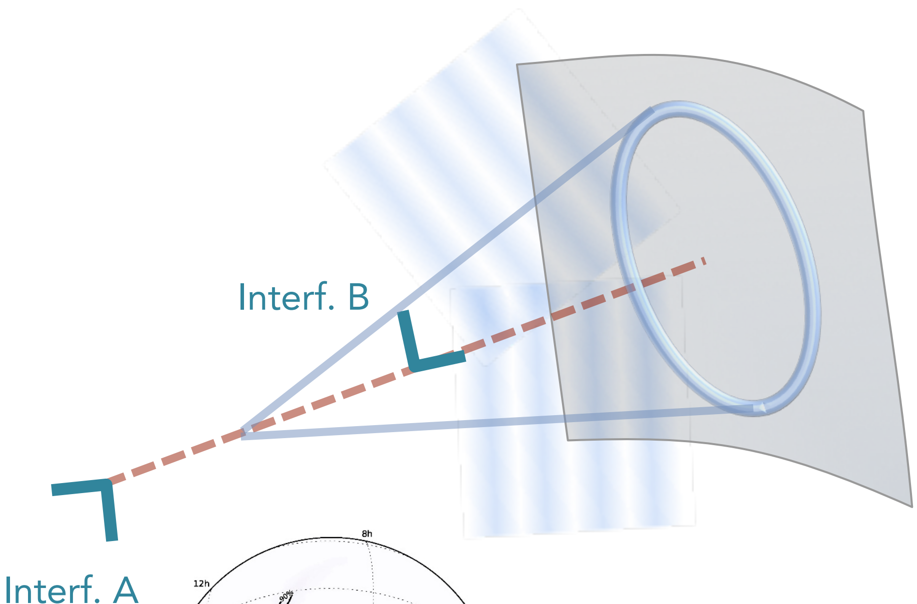
        ➔ Amplitude and phase modulation
  - ***Merger and ringdown***
    - Primarily governed by final black hole mass and spin
    - Masses and spins of binary fully determine mass and spin of final black hole in general relativity

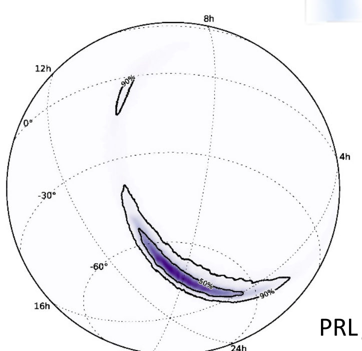
Extrinsic Parameters

- Amplitude depends on masses, distance, and geometrical factors
  - Distance – inclination degeneracy

arXiv:1606.04856 [gr-qc]





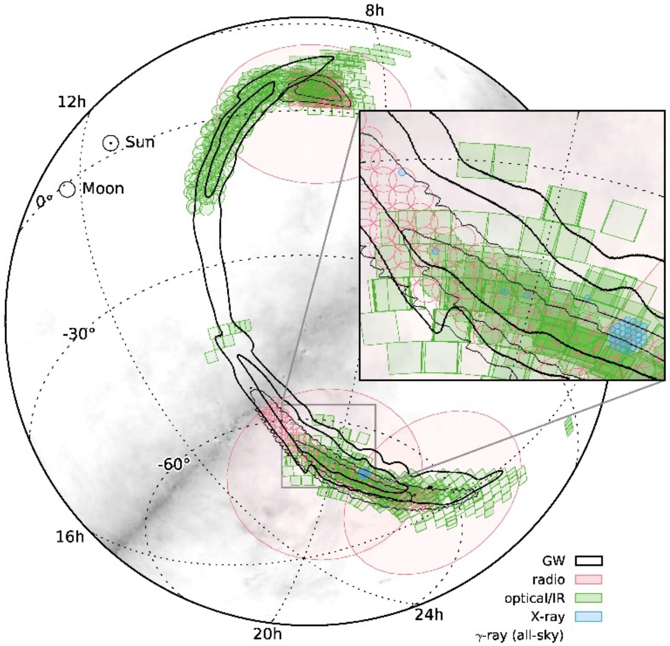


PRL 116, 241102 (2016)

- Source location on the sky
  - inferred primarily from
    - time of flight $6.9^{+0.5}_{-0.4}\ \mathrm{ms}$ for GW150914
    - amplitude and phase consistency
  - Limited accuracy with two detector network
  - 2-D 90% credible region $230\ \mathrm{deg}^2$ (GW150914)
  - 3-D uncertainty volume contains ~10^5 Milky Way equivalent galaxies

Multi-messenger astronomy

- LVC called for EM observers to join a follow-up program
  - LIGO and Virgo promptly share interesting triggers
  - 70 MoUs, 160 instruments covering full spectrum
    - (from radio to very high energy gamma-rays)



ApJ Letters, 826:L13, 2016 July 20

- 25 teams reported follow-up observation of GW150914

- We analyzed thoroughly data around the times of interesting Gamma Ray Bursts -> no signal (up to now)

- This is the birth of multi-messenger astronomy with GW !

(even if we didn't see anything in coincidence)

Testing GR

- Most relativistic binary pulsar known today
  - J0737-3039, orbital velocity $v/c \sim 2 \times 10^{-3}$
- GW150914
  - Strong field, non linear, high velocity regime $v/c \sim 0.5$

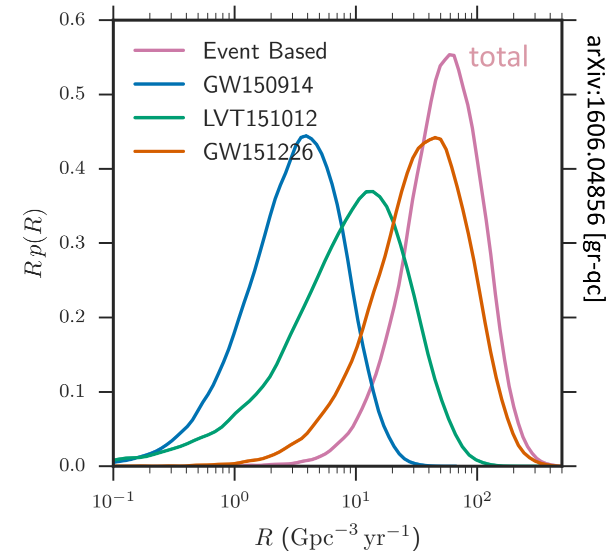
- "Loud" SNR -> coarse tests
  - Waveform internal consistency check
  - No evidence for deviation from General Relativity in waveform
  - Bound on Compton wavelength (graviton mass)
    - No evidence for dispersion in signal propagation

$$\left(\frac{v}{c}\right)^2 = 1 - \left(\frac{hc}{\lambda_g E}\right)^2 \qquad \lambda_g > 10^{13}\ \mathrm{km} \qquad m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$

- More contraining than bounds from the solar system
- Less constraining than model dependent bounds from large scale dynamics of galactic clusters

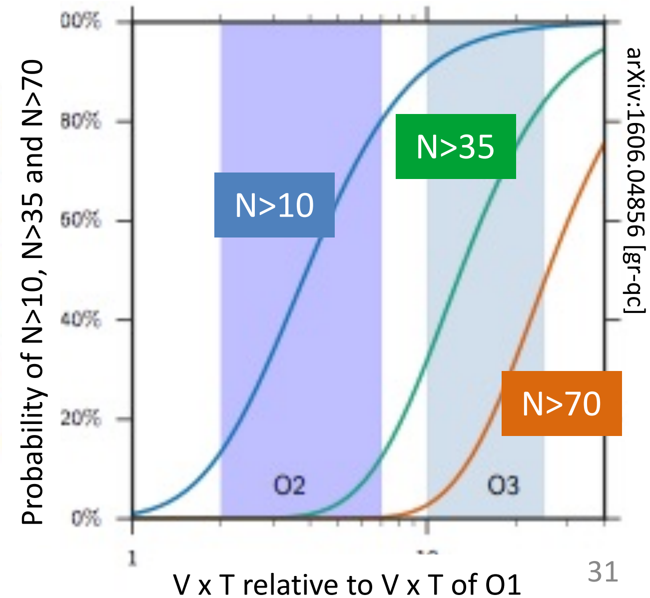
Rate of BBH mergers

- Astrophysical rate inference
  - Counting signals in experiment
  - Estimating sensitivity to population of sources
    - Depends on mass distribution (hardly known)



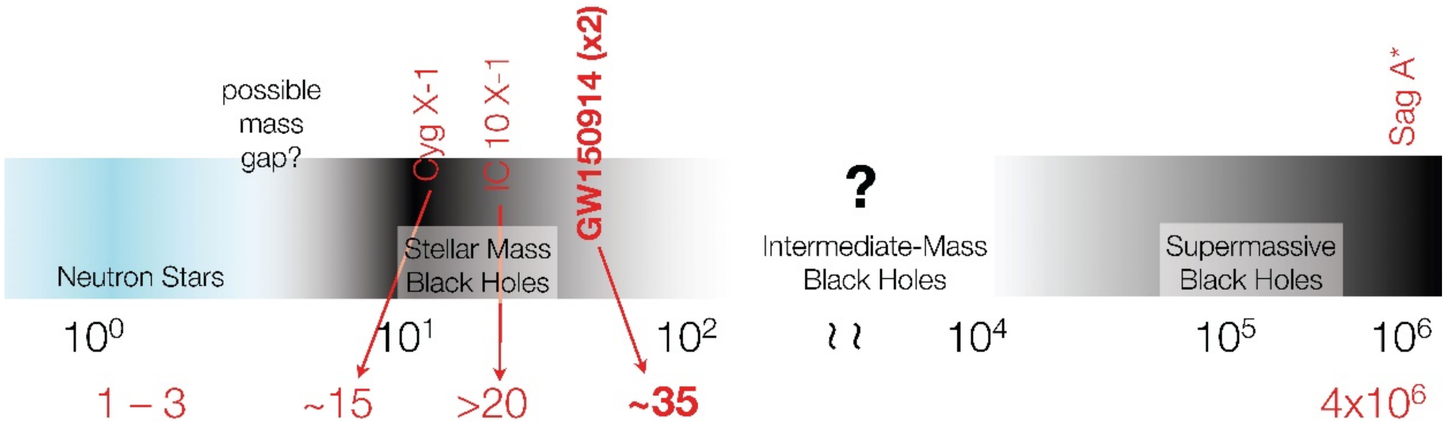
- Low statistics and variety of assumptions -> broad rate range
  - R ~ 9 – 240 Gpc^{-3} yr^{-1}
  - Previsously : R ~ 0.1 – 300 Gpc^{-3} yr^{-1} (electromagnetic observations and population modeling)

- Project expected number of highly significant events as a function of surveyed time x volume



Astrophysics implications

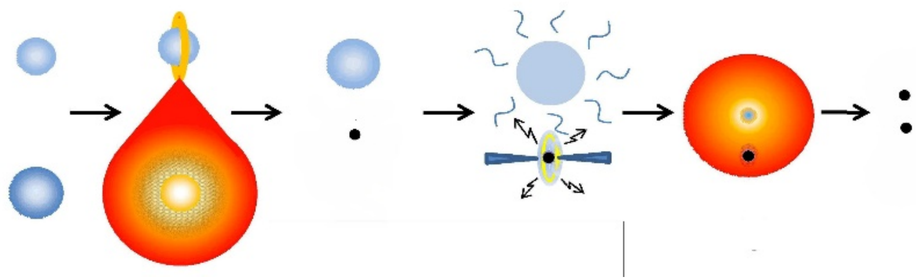
- Relatively massive black holes (> 25 $M_\odot$) exist in nature

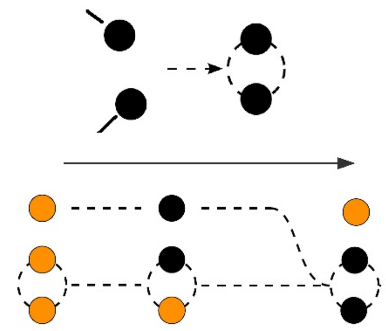


- Massive progenitor stars
  => low mass loss during its life
  => weak stellar wind
- Metallicity = proportion of elements heavier than He
  - High metallicity => strong stellar wind
- => formation of progenitors
  in a low metallicity environment

Astrophysics implications

- Binary black holes form in nature
  - Formation :
    - Isolated binaries
    - Dynamical capture (dense stellar regions)
  - Detected events do not allow to identify formation channel
    - Future : information on the spins can help





- Binary Black Holes merge within age of Universe at detectable rate
  - Inferred rate consistent with higher end of rate predictions ($> 1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$)

What science to do ?

- What we already discovered
  - Gravitational waves do exist !
  - Stellar mass black holes exist in nature !
  - With masses higher than expected
  - And in binaries

- Yet to be discovered
  - GW emitted by binary neutron star or NS-BH mergers
  - GW emitted by spinning neutron stars
  - GW from the stochastic background
  - GW from supernovae
  - GW surprise !

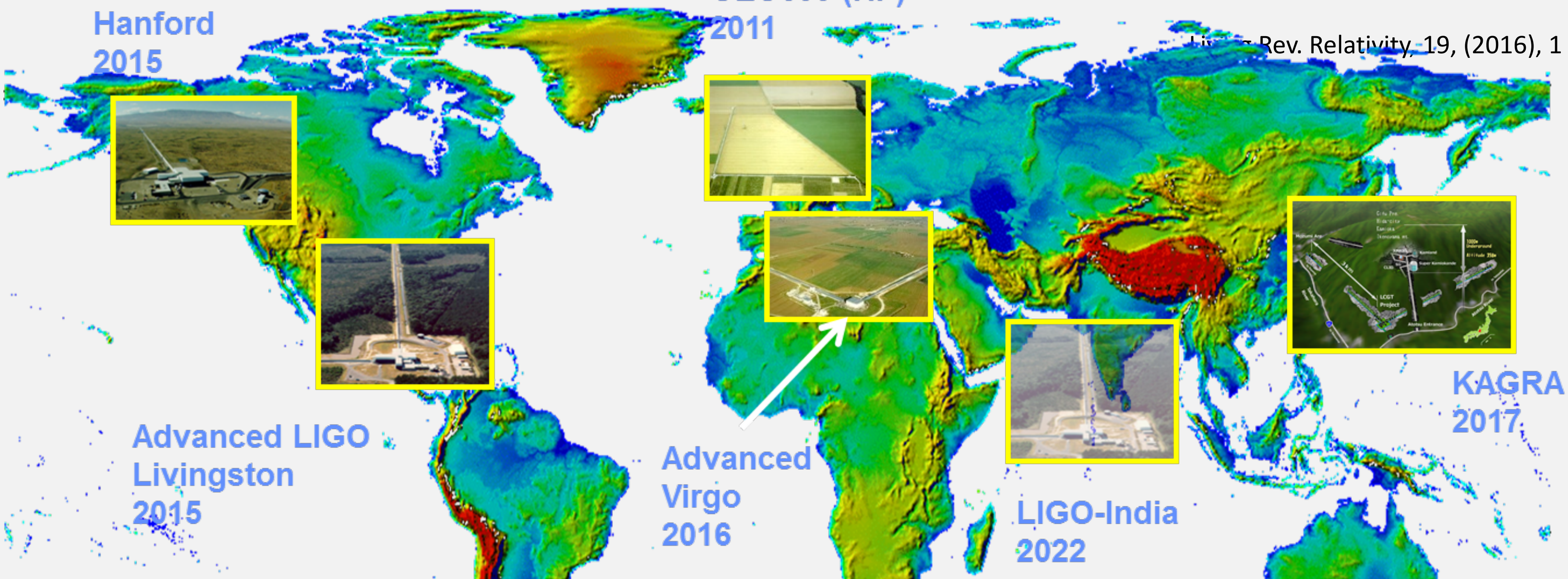
What science to do ?

- Astrophysics
  - Black hole studies
    - Population studies (masses, spins), rates
    - Birth place, binary formation scenario
  - Neutron star studies (Equation Of State…)
  - Star explosion mechanisms

- Fundamental physics
  - Tests of General Relativity
  - Studies of (very) strong gravitational field physics

- Cosmology
  - Determination of the Hubble constant
  - Evolution of population with the redshift

A glimpse at the future



Living Rev. Relativity, 19, (2016), 1

Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	$> 1-2$	$> 3-8$	> 20
		20 deg^2	< 1	14	> 10	$> 8-30$	> 50
	median/deg^2		480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
	median/deg^2		88	29	—	—	—

Conclusion

- Second generation ground-based GW detectors came back online
- Amazing sensitivity
- The LIGO detectors observed three clear and loud signals : GW150914, GW151226 and GW170104,and a candidate LVT151012
- Interpreted as
  - GW150914 : coalescence of two black holes of 29 and 36 solar masses, located at a distance of 1.3 Glyr
  - GW151226 : coalescence of two black holes of 7 and 14 solar masses, located at a distance of 1.4 Glyr
  - GW170104 : coalescence of two black holes of 19 and 31 solar masses, located at a distance of 2.8 Glyr

- This discovery opens up new paths
  - Testing gravitation in uncharted territory
  - Gravitational wave astronomy / astrophysics and cosmology

- Eagerly waiting for – and striving for – Advanced Virgo to join the network and the fun

- Spares

O1 run

- September 12, 2015 – January 12, 2016
  - Preceded by engineering run ER8 – from Aug 17
  - Stable data taking from Sep 12
  - O1 scheduled to start on Sep 18
    - When fully ready with calibration / hardware injections / EM follow-up alerts / computing

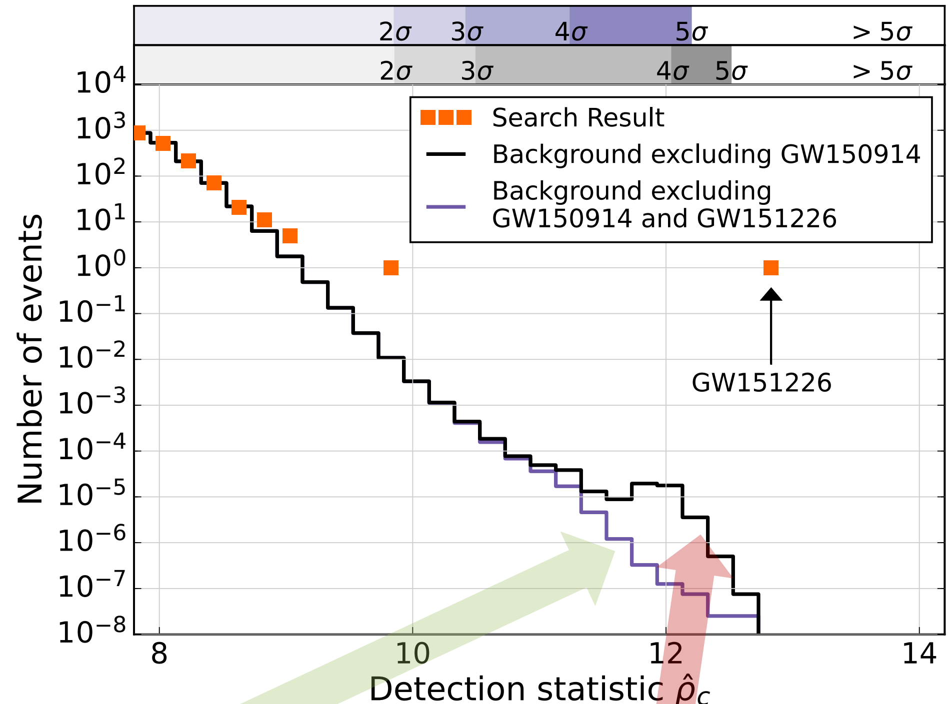
  - 51.5 days of coincident data
    - H1 = LIGO Hanford, L1 = LIGO Livingston

CBC BBH search result : GW151226

- GW151226 is the second loudest event in the search, $\hat{\rho}_c = 12.8$

  - Remove all triggers associated with GW150914 (confidently identified as GW) from background calculation

  - Significance $> 5.3\sigma$



PRL 116, 241103 (2016)

Background excluding contribution from GW150914 and GW151226 (gauge significance of other triggers)

Coincidences between single detector triggers from GW151226 and noise in other detector (excluding GW150914 triggers)

CBC BBH search result : LVT151210

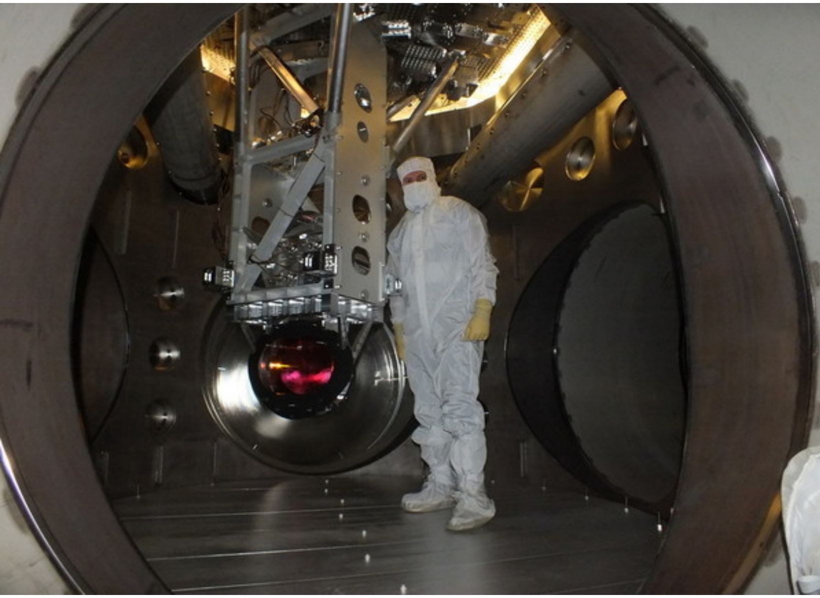
- Third most significant event in the search,

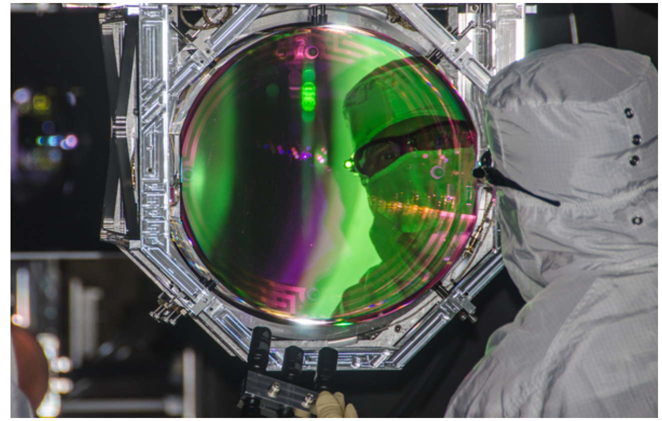
$\hat{\rho}_c$ = 9.7

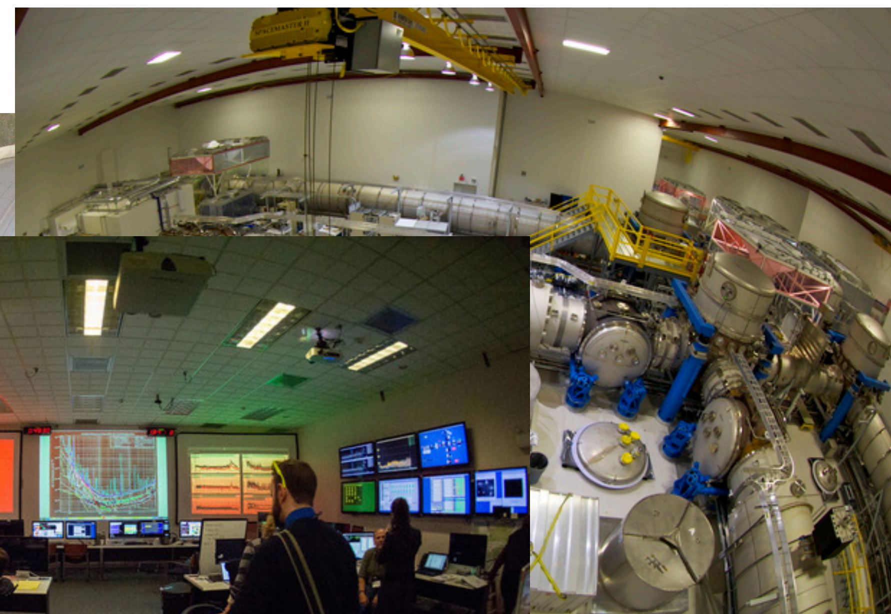
- Significance $2\,\sigma$ in one of the analyzes
- No instrumental/environmental artefact
- Parameter estimation results consistent with astrophysical BBH source

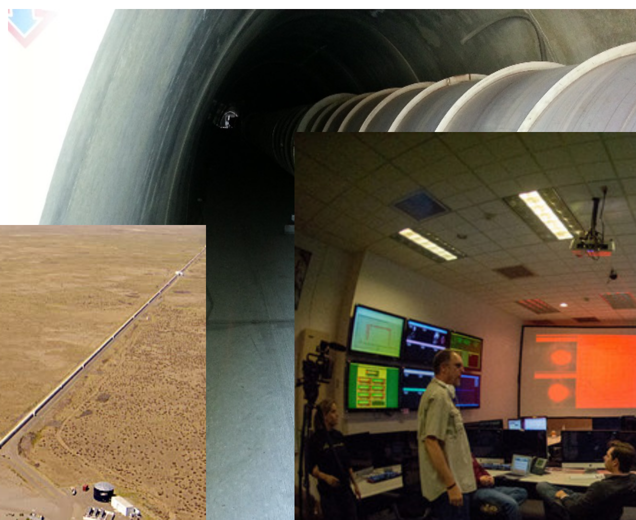
What does Virgo look like ?

What does LIGO look like ?





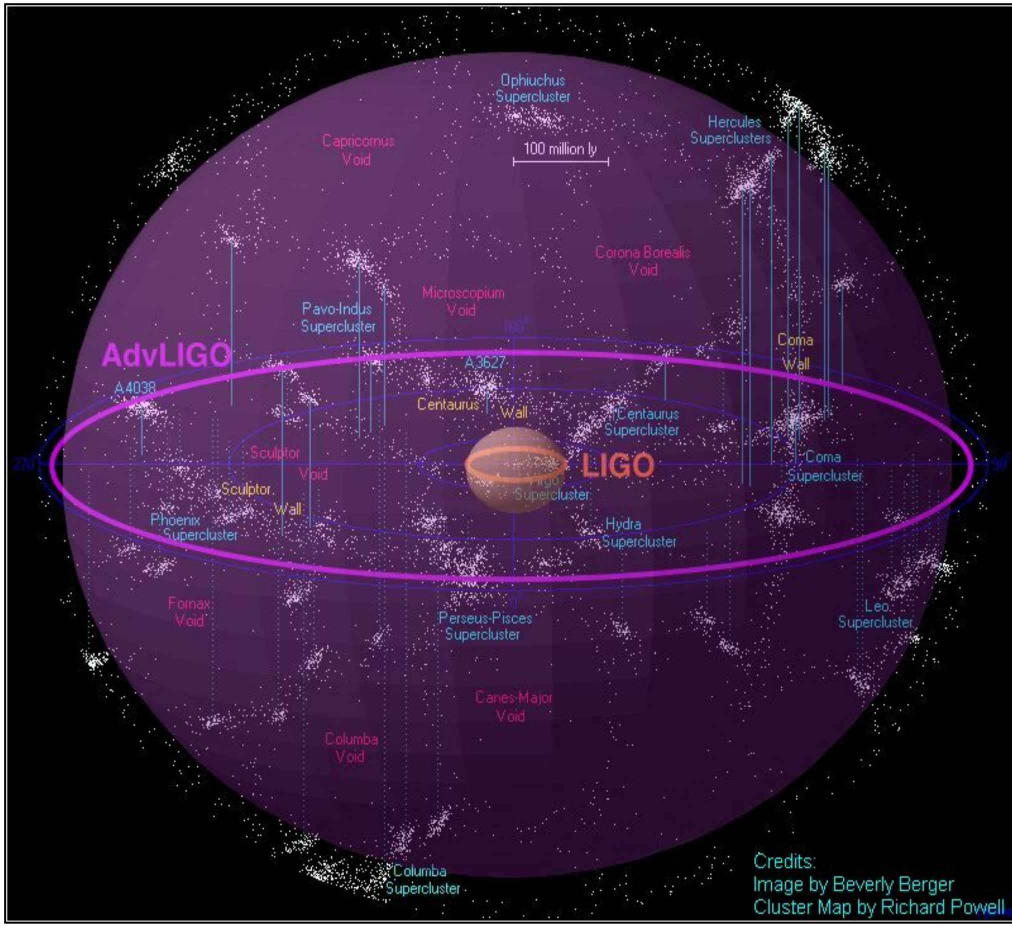




- Horizon = distance at which a reference compact body coalescence gives a SNR (Signal over Noise Ratio) of 8 in the detectors

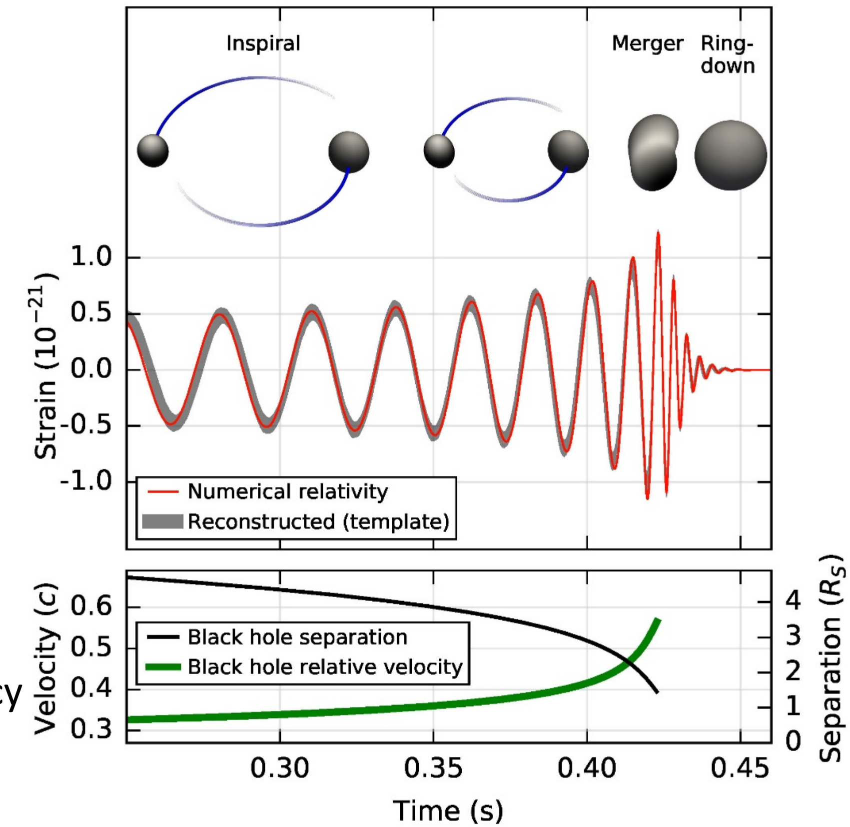
- Picture : reference = 2 x 1.4 $M_{\odot}$ neutron star coalescence, average orientation

- Sensitivity x 10 ⇔ Sensitive volume x 10^3



Black holes coalescences ? Yes !

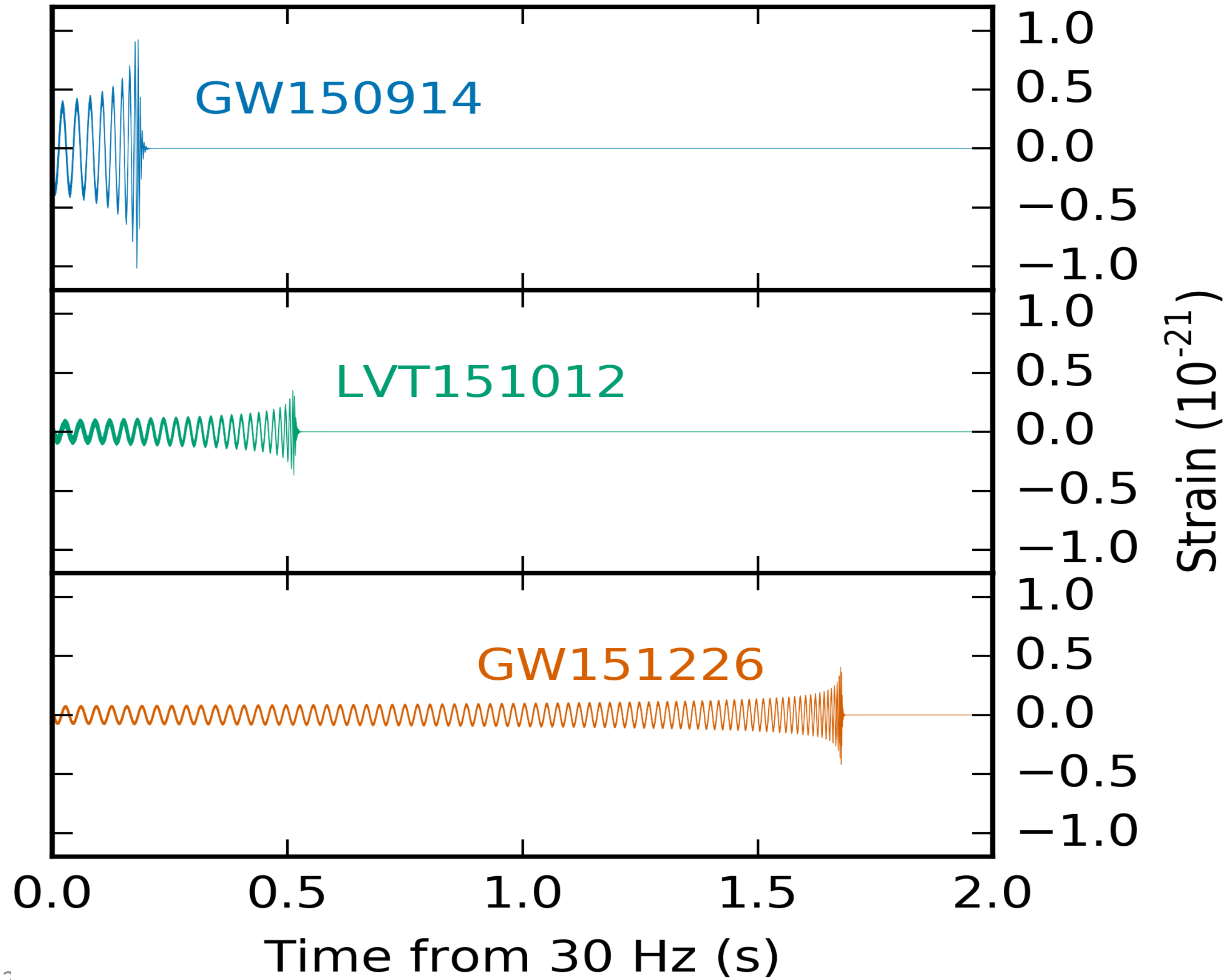
- Example of GW150914
- Over 0.2 s, frequency and amplitude increase from 35 Hz to f_{peak} = 150 Hz (~ 8 cycles)
  - Reminder : the "chirp mass" characterizes the inspiral phase
  - Finds $\mathcal{M} \simeq 30 M_\odot$,
    $$M = m_1 + m_2 \gtrsim 70 M_\odot$$
  - Keplerian separation gets close to Schwarzschild radius
    $$R_S = 2GM/c^2 \gtrsim 210 \text{ km}$$
  - Very close and compact objects
    - BNS too light, NSBH merge at lower frequency



- Decay of waveform after peak
  - consistent with damped oscillations of BH (relaxing to final stationary Kerr configuration)
  - SNR too low to claim observation of quasi normal modes

Matching waveform examples

- From 30 Hz
  - Start of the sensitive band of detectors



Parameter Estimation

- Intrinsic parameters (8)
  - Masses (2) + Spins (6)
- Extrinsic parameters (9)
  - Location : luminosity distance, right ascension, declination (3)
  - Orientation: inclination, polarization (2)
  - Time and phase of coalescence (2)
  - Eccentricity (2)

- PE (parameter estimation) based on coherent analysis across detector network
  - Bayesian framework: Computes likelihood of data given parameter
  - Based on match between data and predicted waveform
  - Explores full multidimensional parameter space with fine stochastic sampling

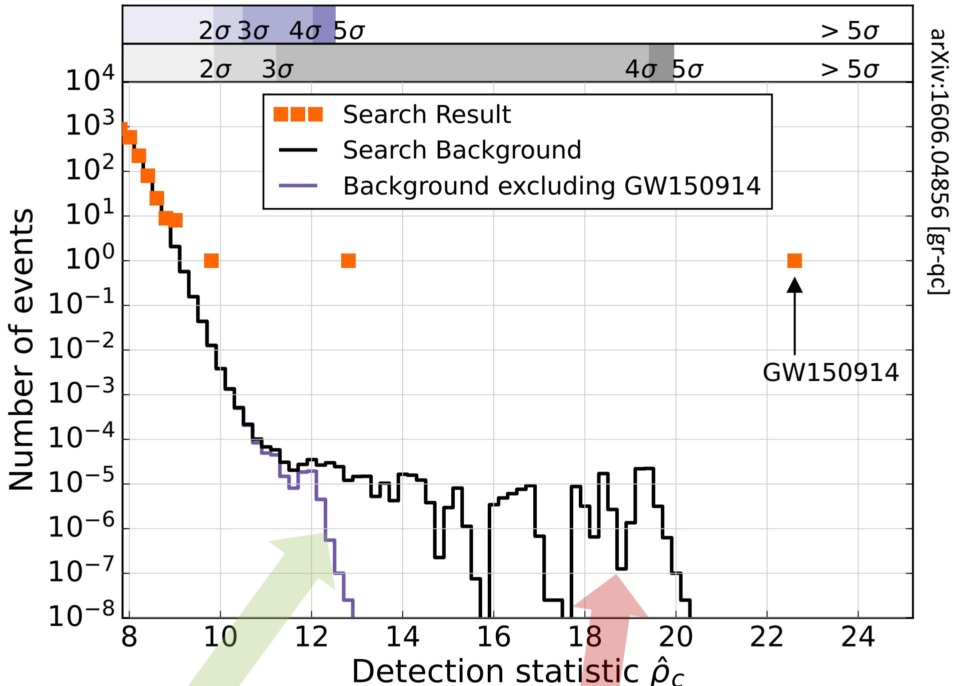
- PE relies on accurate waveform models
  - Crucial progress over past decade to model all phases of BBH coalescence: Inspiral, Merger, Ringdown (IMR)
  - Waveform models combine perturbative theory and numerical relativity
    - EOBNR: Aligned spins (11 parameters)
    - IMRPhenom: Aligned spins + one effective precession spin parameter (12 parameters)
  - Still missing: eccentricity, higher order gravitational modes, full spin generality

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

- Masses
- Spins
  - Weakly constrained
- Radiated energy
- Peak luminosity

CBC BBH search result : GW150914

- Statistic
  - $\hat{\rho} = \rho / \{[1 + (\chi_r^2)^3]/2\}^{1/6}$
  - $\hat{\rho}_c = \sqrt{\hat{\rho}_{H1}^2 + \hat{\rho}_{L1}^2}$
- Significance
  - GW150914 is the loudest event in the search, $\hat{\rho}_c = 22.7$
  - Individual triggers in L1 and H1 (forming GW150914): highest $\hat{\rho}$ in each detector
  - Significance $> 5.3\sigma$

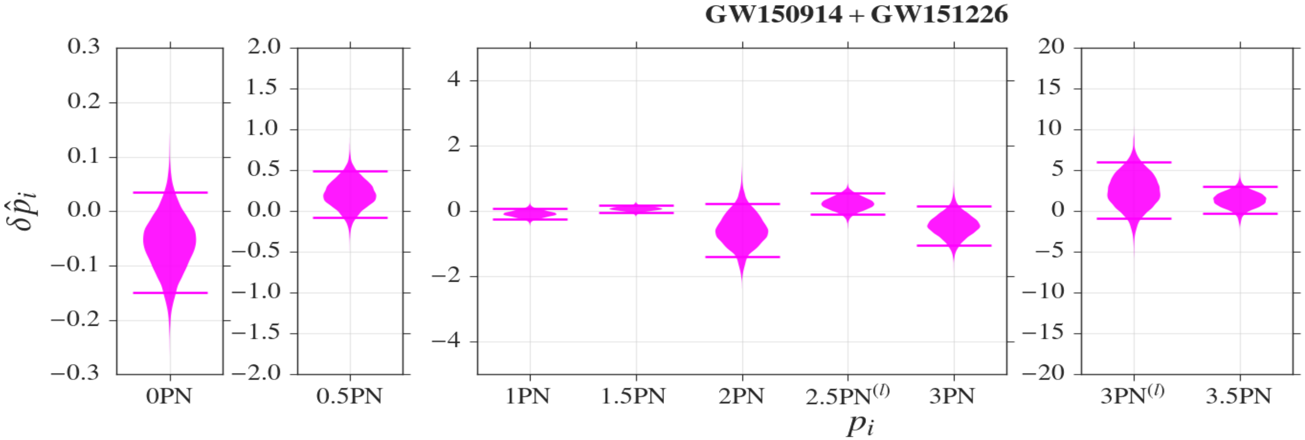


Background excluding contribution from GW150914 (gauge significance of other triggers)

Coincidences between single detector triggers from GW150914 and noise in other detector

Testing GR with GW150914 (II)

- No evidence for deviation from GR in waveform



arXiv:1606.04856 [gr-qc]

- No evidence for dispersion in signal propagation
  - Bounds :

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

$$m_g \leq 1.2 \times 10^{-22}\ \text{eV/c}^2$$

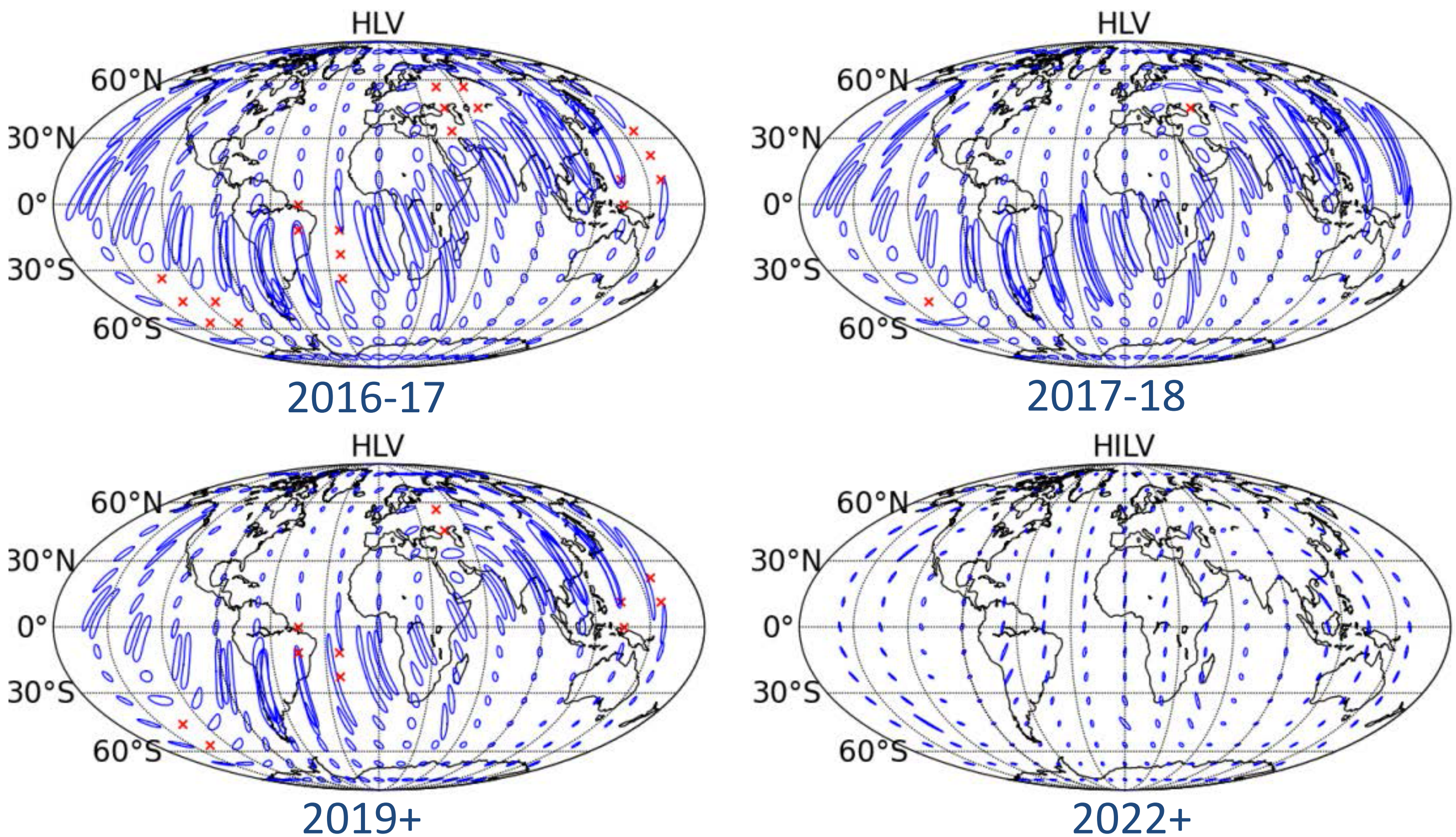
$$\left(\frac{v}{c}\right)^2 = 1 - \left(\frac{hc}{\lambda_g E}\right)^2$$

  - More constraining than bounds from
    - Solar System observations
    - binary pulsar observations
  - Less constraining than model dependent bounds from
    - large scale dynamics of galactic clusters
    - weak gravitational lensing observations

Future Localization Prospects

Face-on BNS
@ 80 Mpc

Face-on BNS
@ 160 Mpc



HLV = Hanford-Livingston-Virgo

HILV = Hanford-LIGO India-Livingston-Virgo

From one generation to the next (II)

Terrestrial detectors

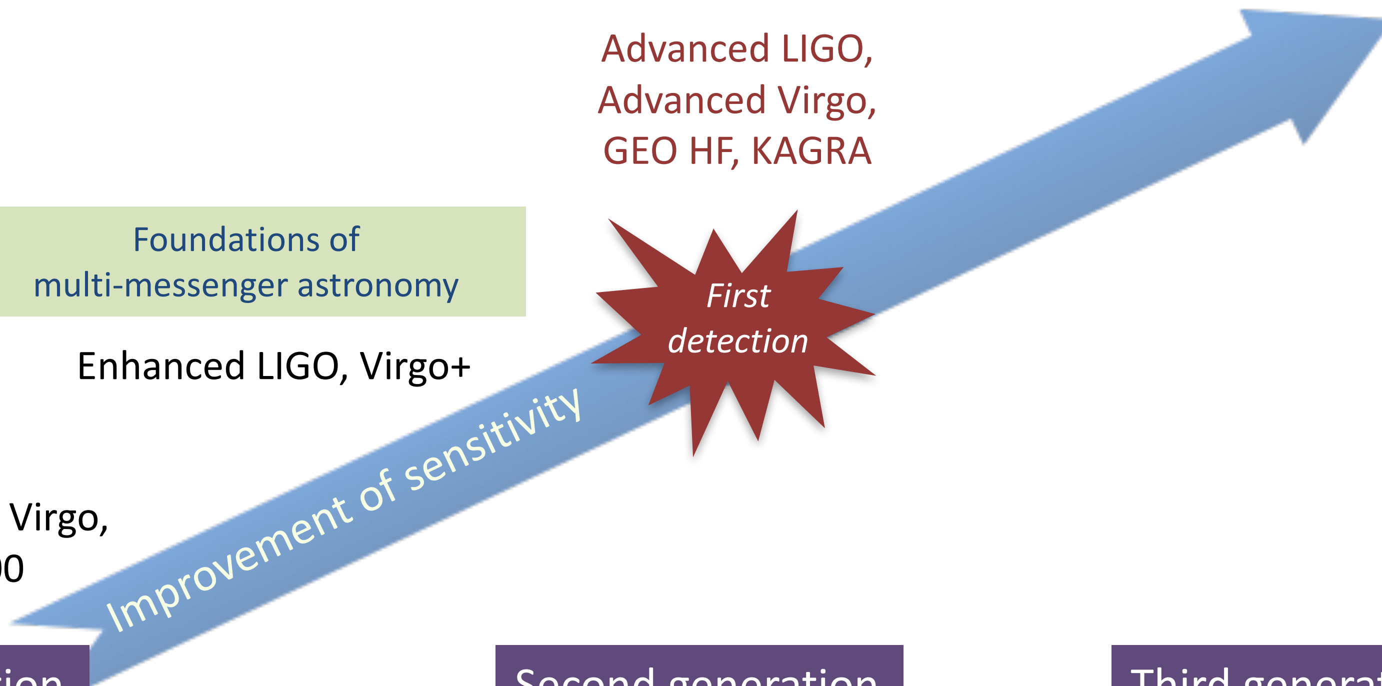
Einstein Telescope (ET)

Advanced LIGO,
Advanced Virgo,
GEO HF, KAGRA

Foundations of
multi-messenger astronomy

Enhanced LIGO, Virgo+

Initial LIGO, Virgo,
GEO600



First generation

Data taking
Rates upper limits
Building the network

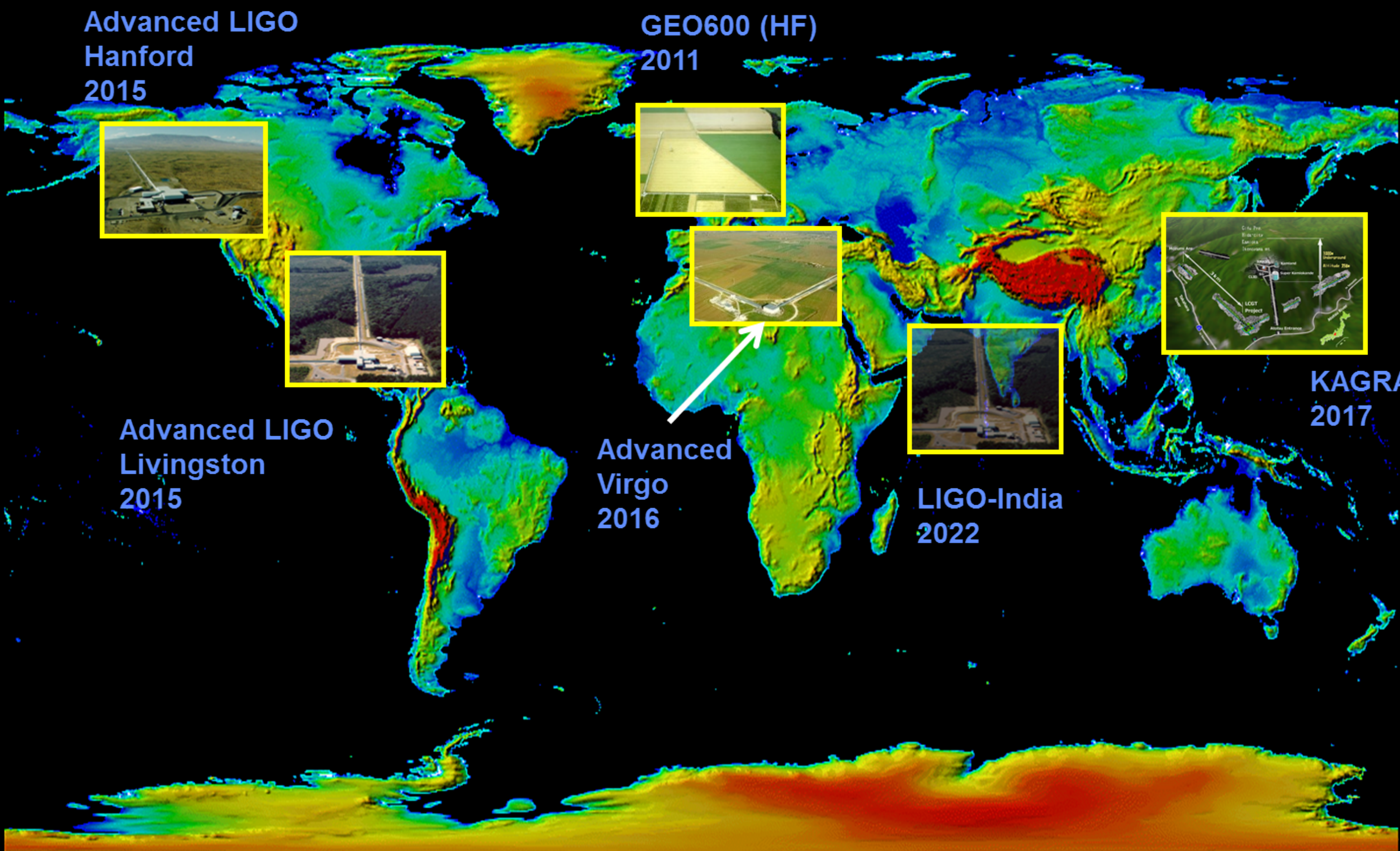
Second generation

Towards routine observations,
GW astronomy

Third generation

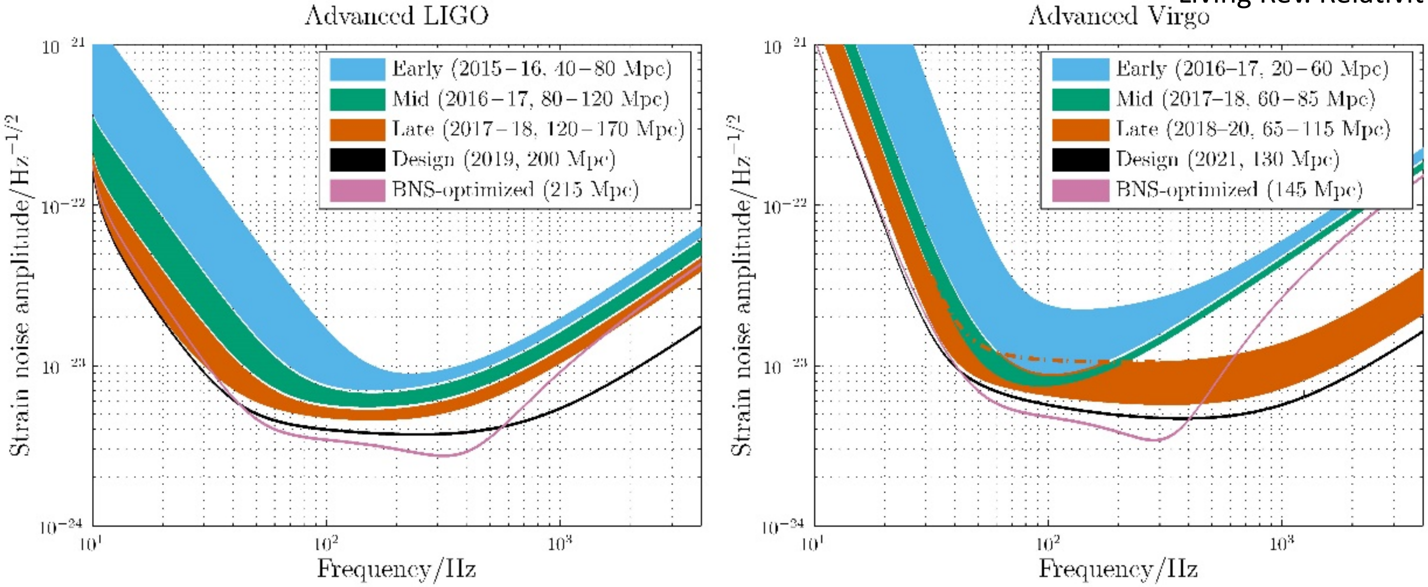
In-depth observation of
the universe with GW

2nd Generation Network



Plan and sensitivity evolution

Living Rev. Relativity, 19, (2016), 1



Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
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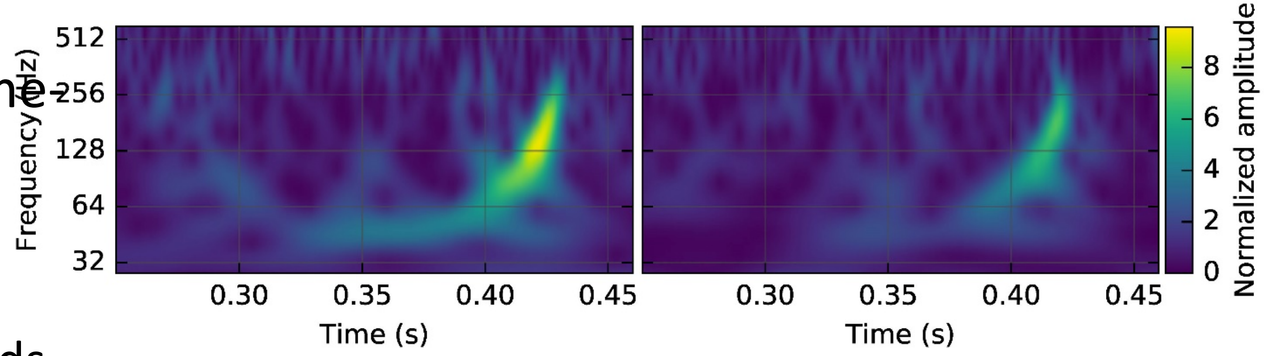
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	*> 1 – 2*	*> 3 – 8*	*> 20*
		20 deg^2	< 1	14	*> 10*	*> 8 – 30*	*> 50*
		median/deg^2	480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
		median/deg^2	88	29	—	—	—

Generic Transient Search

- Operates without a specific search model
- Identifies coincident excess power in time-frequency representations of h(t)
  - Frequency < 1 kHz
  - Duration < a few seconds



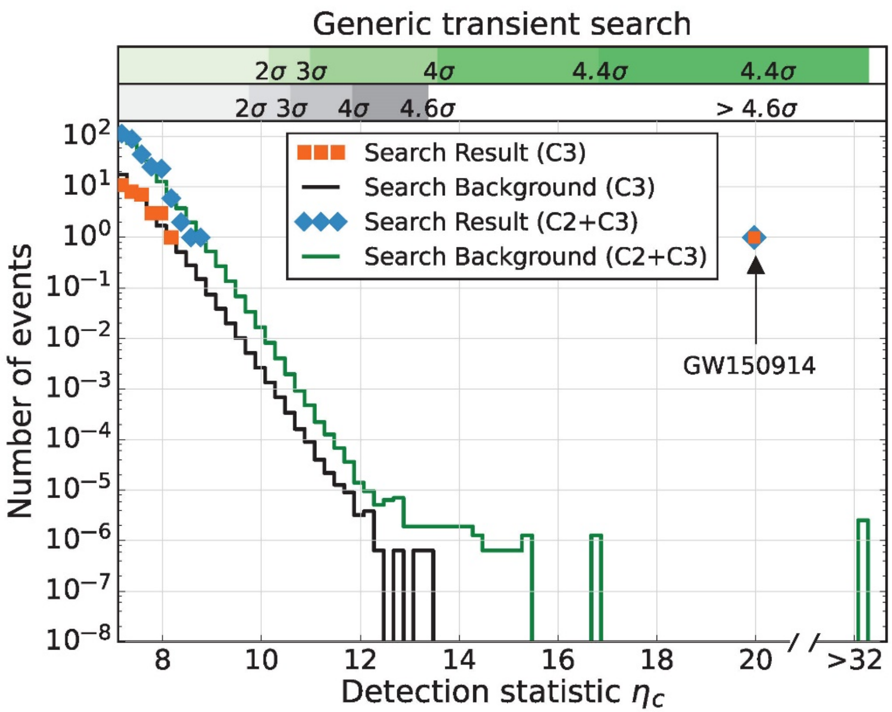
- Reconstructs signal waveforms consistent with common GW signal in both detectors using multi-detector maximum likelihood method
- Detection statistic
  - $$\eta_c = \sqrt{\frac{2E_c}{(1+E_n/E_c)}}$$

E_c: dimensionless coherent signal energy obtained by cross-correlating the two reconstructed waveforms
E_n: dimensionless residual noise energy after reconstructed signal is subtracted from data

- Signals divided into 3 search classes based on their time-frequency morphology
  - C3 : Events with frequency increasing with time – CBC like

Generic Transient Search Result

- GW150914 loudest event in C3 search class, $\eta_c = 20$
- Significance also measured from time slides
  - T_{bckd} = 67,400 yr , trial factors
  - FAR < 1 per 22,500 yr
  - FAP < 2 10^{-6} ➔ > 4.6 σ

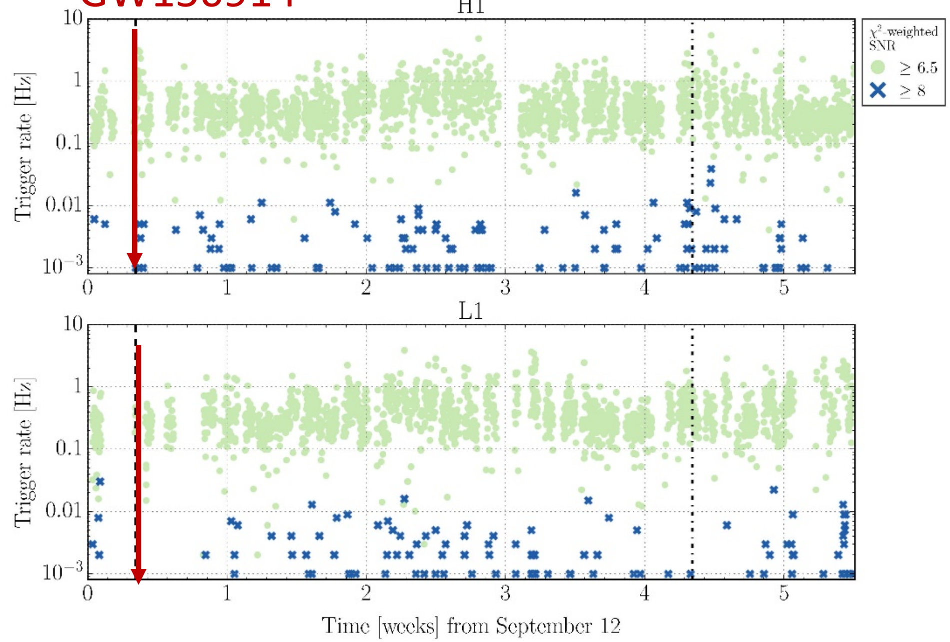


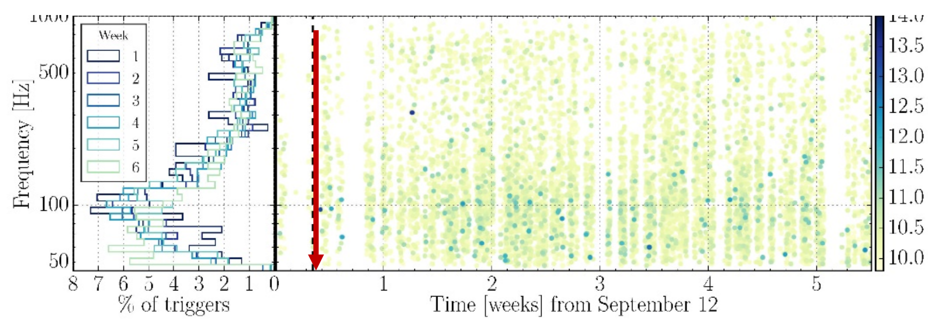
Data quality

- On analyzed period
  - Clean data set
  - Homogeneous background

- Data quality vetoes
  - Identify periods with intrumental or environmental problems
  - Veto those periods

  - GW150914 >> every background event even without DQ vetoes



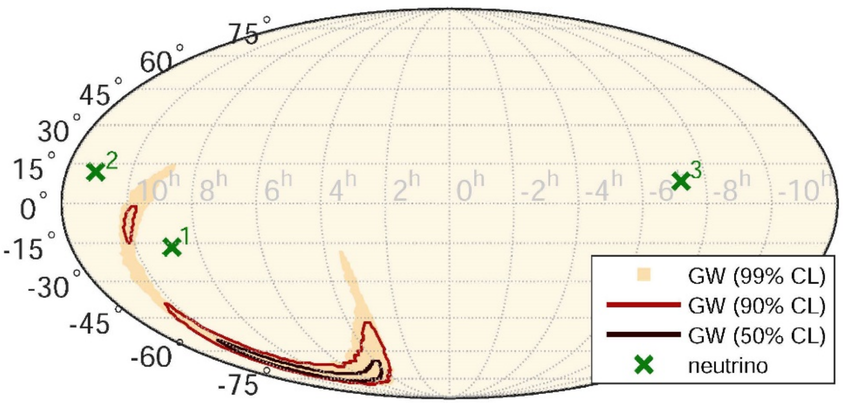


GW150914

Hanford			Livingston		
DQ veto category	Total deadtime (s)	% of total coincident time	DQ veto category	Total deadtime (s)	% of total coincident time
1	73446	4.62%	1	1066	0.07%
2	5522	0.35%	2	87	0.01%

High-Energy Neutrino Follow-up

- Search for coincident high energy neutrino candidates in IceCube and ANTARES data
  - HEN ν expected in (unlikely) scenario of BH + accretion disk system
  - Search window ± 500 s



- No ν candidate in both temporal and spatial coincidence
  - 3 ν candidates in IceCube
  - 0 ν candidate in ANTARES
  - Consistent with expected atmospheric background
  - No ν candidate directionally coincident with GW150914

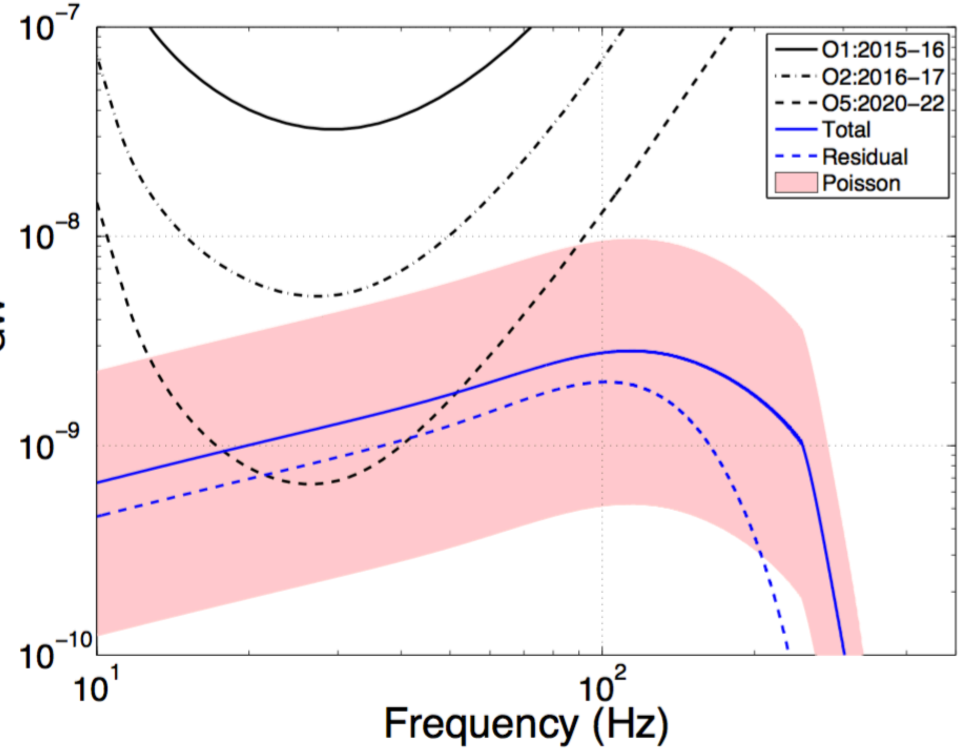
- Derive ν fluence upper limit (direction dependent)
- Derive constraint on total energy emitted in ν by the source
  - $$\mathrm{E}^{\mathrm{ul}}_{\nu,\mathrm{tot}} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{\mathrm{gw}}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

Expected BBH Stochastic Background

- GW150914 suggests population of BBH with relatively high mass
- Stochastic GW background from BBH could be higher than expected
  - Incoherent superposition of all merging binaries in Universe
  - Dominated by inspiral phase
- Estimated energy density

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}$$

$$\Omega_{\rm GW}(f = 25\,{\rm Hz}) = 1.1^{+2.7}_{-0.9} \times 10^{-9}$$



- Statistical uncertainty due to poorly constrained merger rate currently dominates model uncertainties
- Background potentially detectable by Advanced LIGO / Advanced Virgo at projected final sensitivity